Ventilation of the North Atlantic Oxygen Minimum Zone

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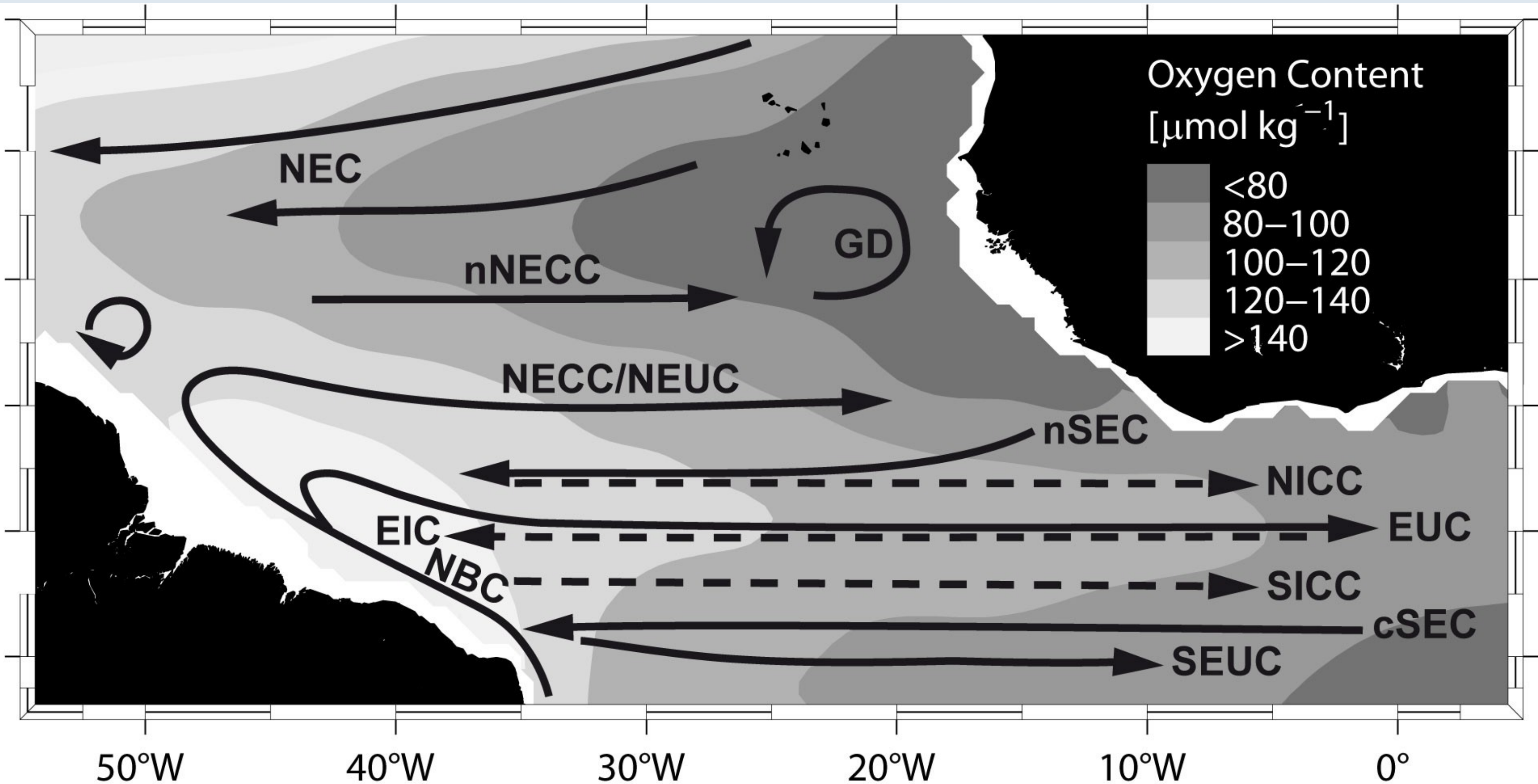
Ventilation of the North Atlantic Oxygen Minimum Zone (OMZ)

Mean Circulation and Oxygen Distribution

Complex zonal current system connects high-oxygen western boundary regime with sluggish flow in the eastern basin.

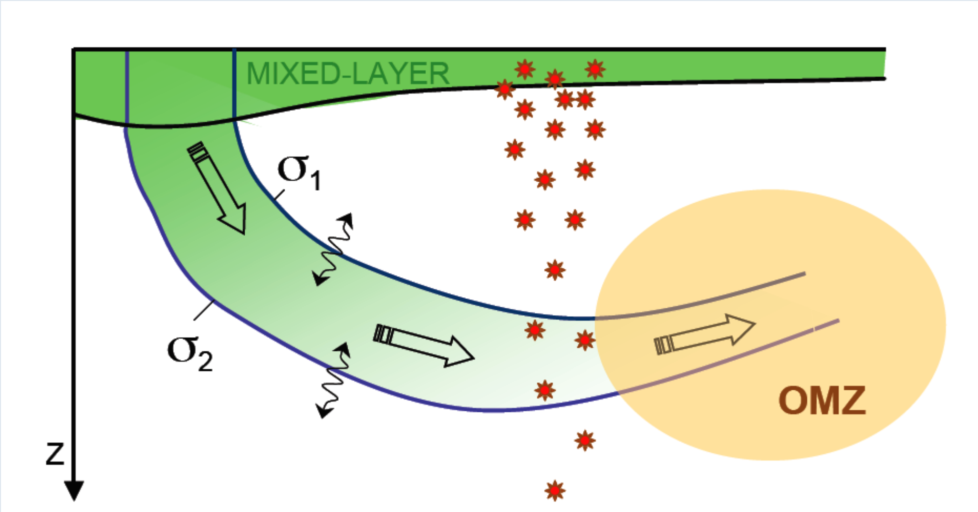


Brandt et al. 2008, 2010

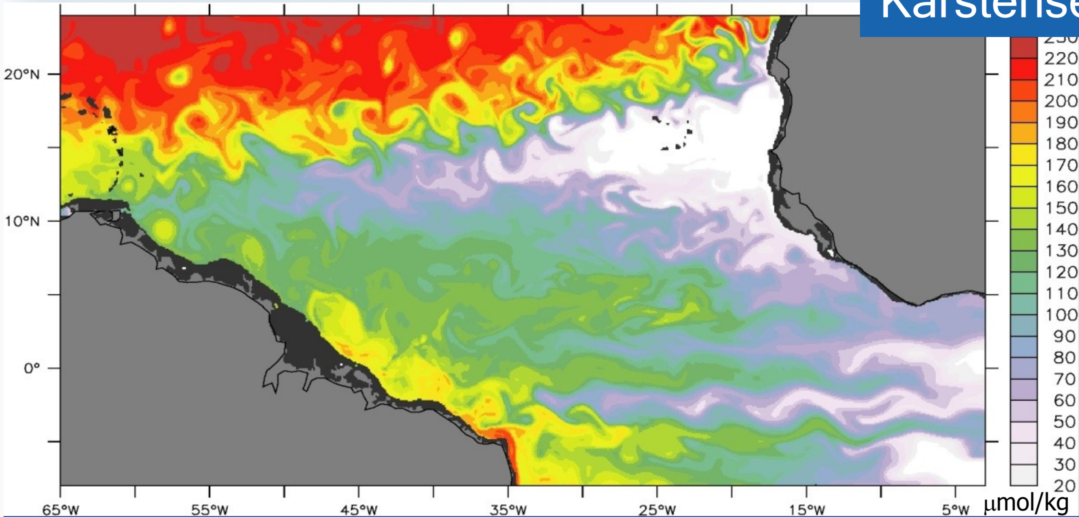
Oxygen Minimum Zones

Oxygen supply along isopycnal surfaces, in general weak diapycnal mixing.

Oxygen consumption via heterotrophic respiration.



Karstensen et al. 2008



FLAME simulation, C. Eden

Mesoscale eddy field play a dominant role in the ventilation of the OMZ.

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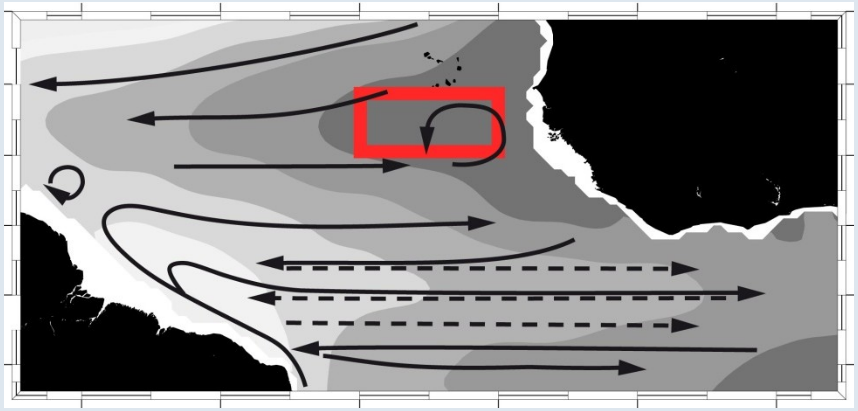
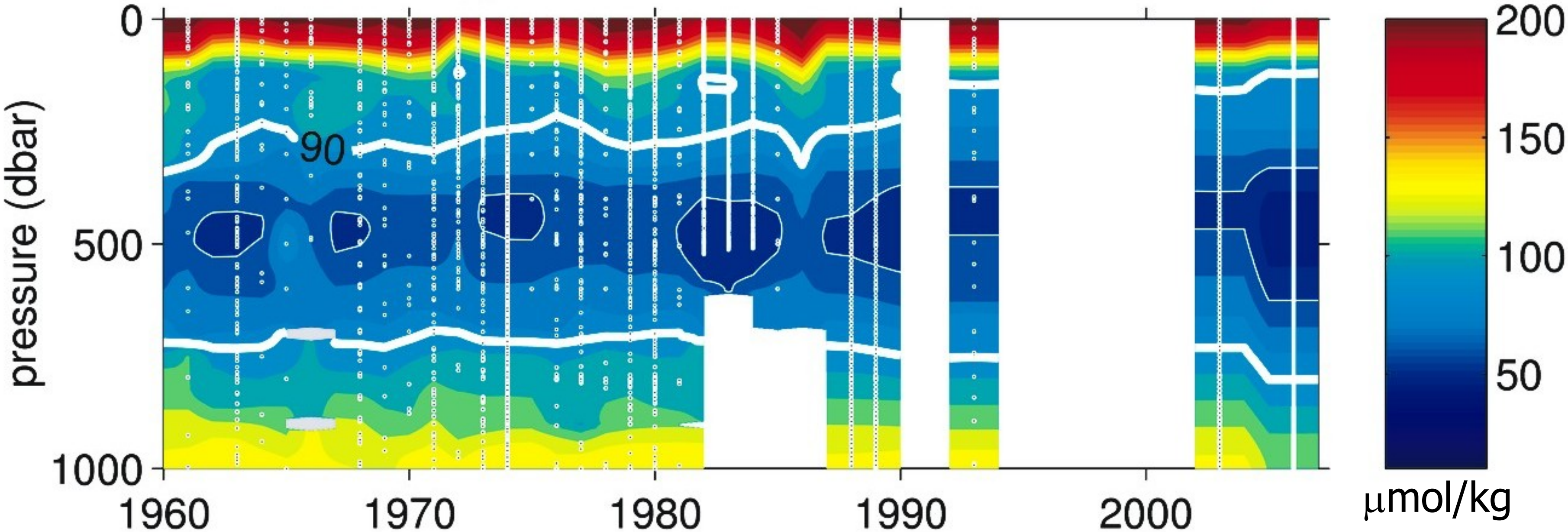
Oxygen Depletion in the North Atlantic OMZ

Oxygen data show a reduction of dissolved oxygen in the North Atlantic OMZ over the last 40 years – stronger than in all other tropical regions.





Stramma et al. 2008

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Mechanisms of Oxygen Depletion

Anthropogenic forcing:

- Increased stratification and corresponding reduction of ventilation
- Solubility changes associated with a warming of subducted water masses (Bopp et al. 2002; Matear and Hirst 2003)
- Increase in heterotrophic respiration along the pathways of ventilating water masses due to excess organic carbon formed at higher CO_2 levels (Oschlies et al. 2008)

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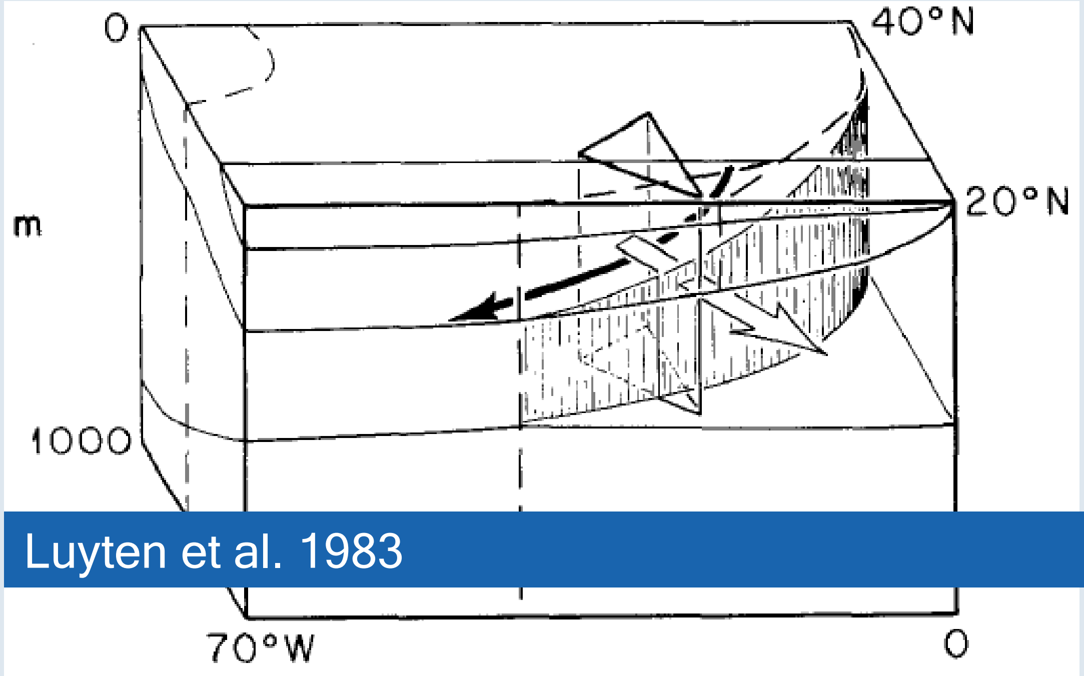
Ventilated Thermocline

Transport processes at the boundary between ventilated and unventilated thermocline:

advection (solid arrow) and diffusive flux (open arrow)



Luyten et al. 1983

What are other physical processes relevant for the ventilation of the OMZ?

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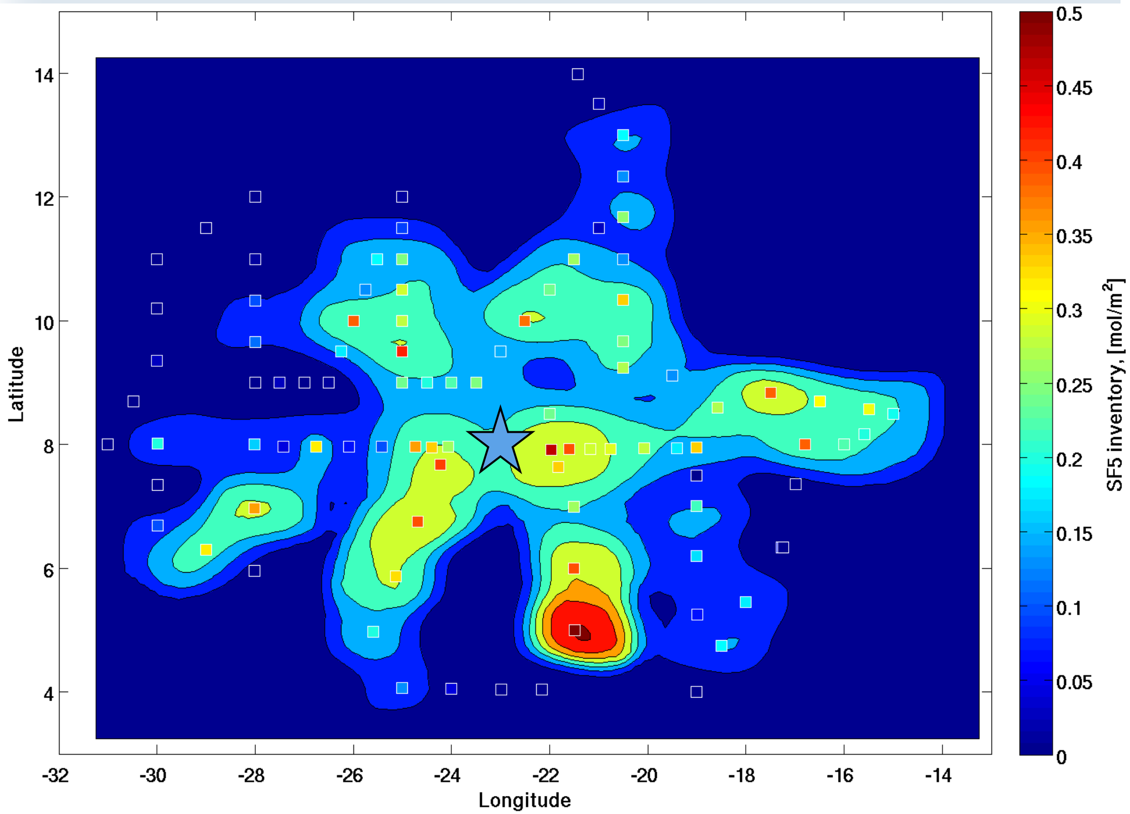
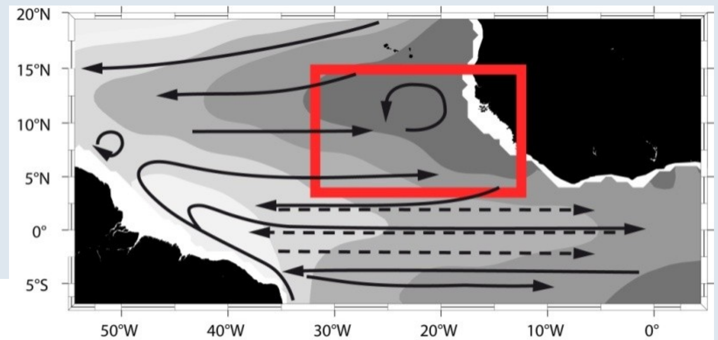
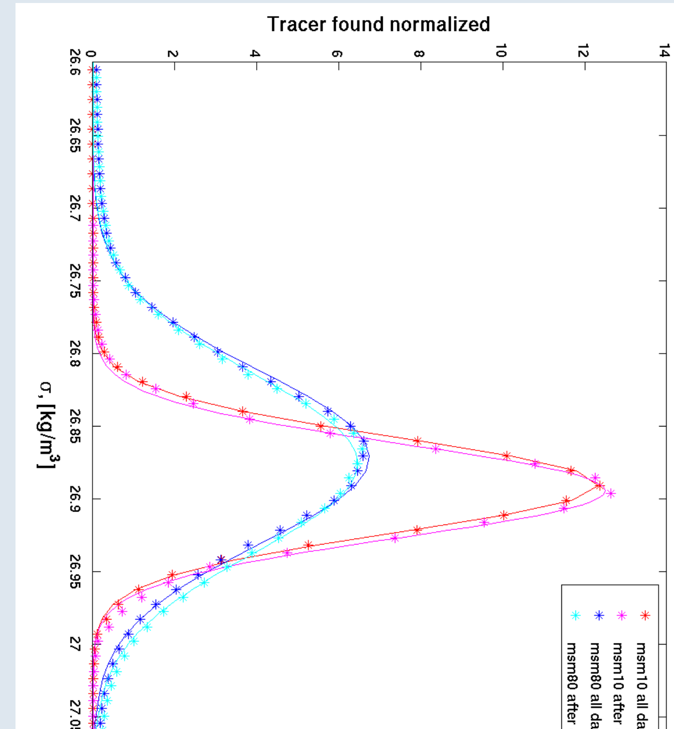
Diapycnal Mixing

Guinea Upwelling Tracer Release Experiment:

K_ρ = 1.0 - 1.3 10^{-5} m^2 s^{-1}



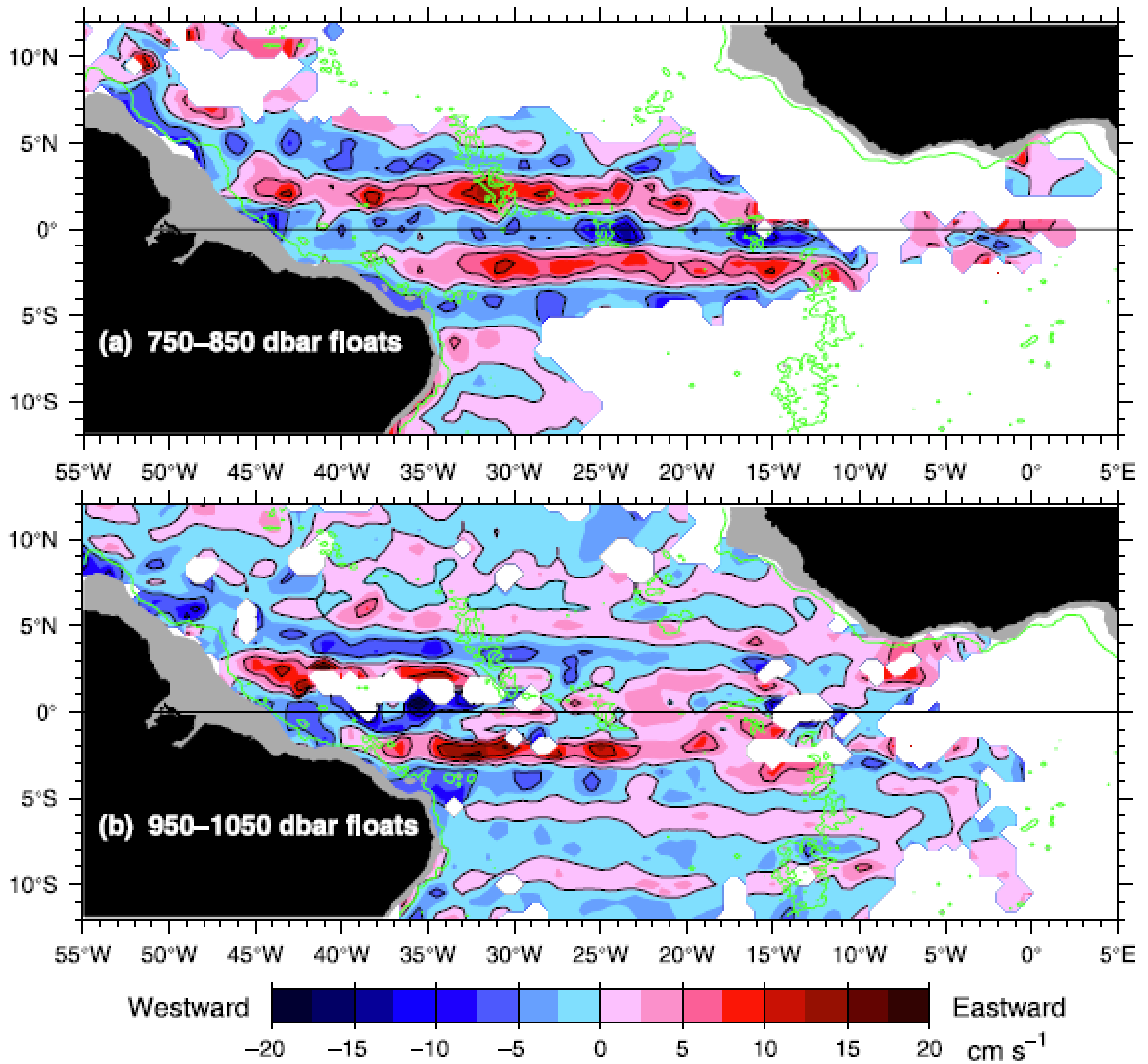




Visbeck et al. 2010

Latitudinally Alternating Zonal Jets in the Tropical Atlantic

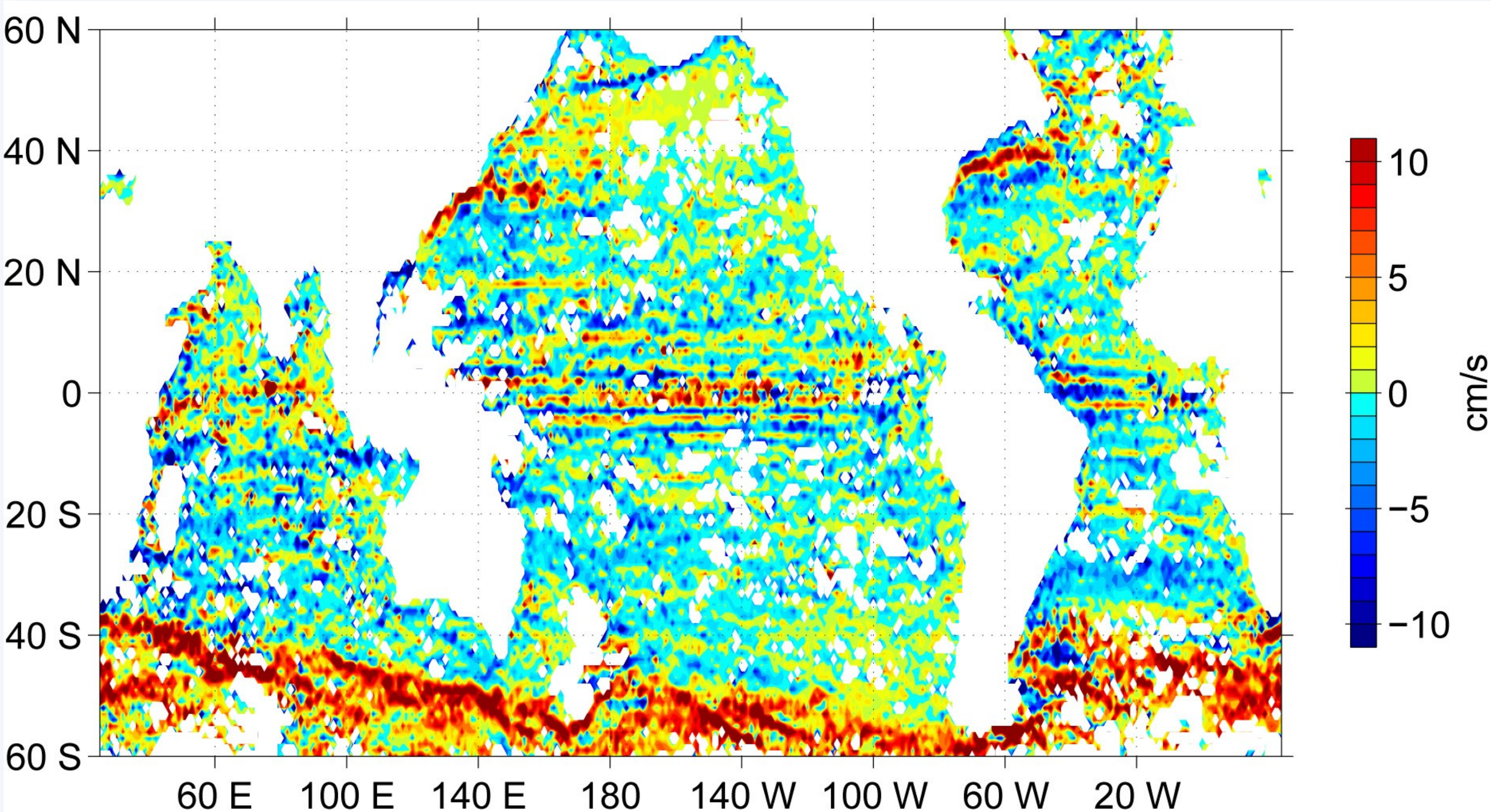
Mean zonal velocity from deep drifting floats at 800 and 1000 m depth.



Ollitrault et al. 2006

Latitudinally Alternating Zonal Jets in the Global Ocean

Mean zonal velocity at 1000 m from ARGO floats (Lebedev et al. 2007).

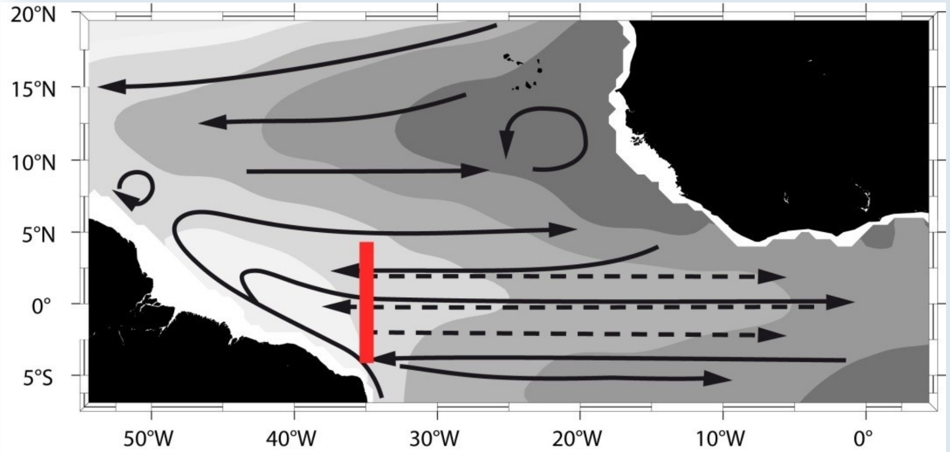


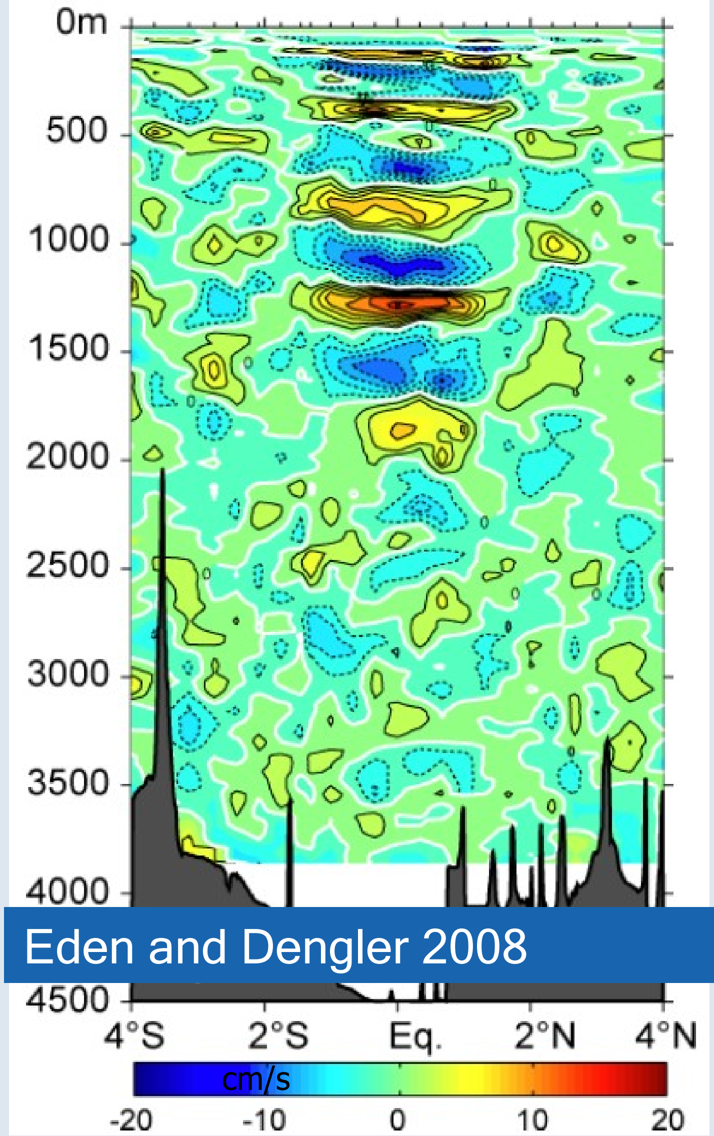
Ascani et al. 2010

Equatorial Deep Jets

Equatorial deep jets or stacked jets are characterized by high baroclinic modes (mode 13-19).

Jets exchange passive tracer between western boundary regime and eastern equatorial Atlantic.





Eden and Dengler 2008

Questions to be Addressed

How is the North Atlantic OMZ ventilated?

How do zonal jets of small vertical or meridional scale contribute to the ventilation?

Are there long-term changes in hydrography and/or zonal flow field associated with changes in the oxygen distribution?

We will use shipboard hydrographic and current sections taken along 23°W between 1999-2008, equatorial current meter moorings at 23°W deployed since 2002 as well as hydrographic profiles obtained between 1972-1985.

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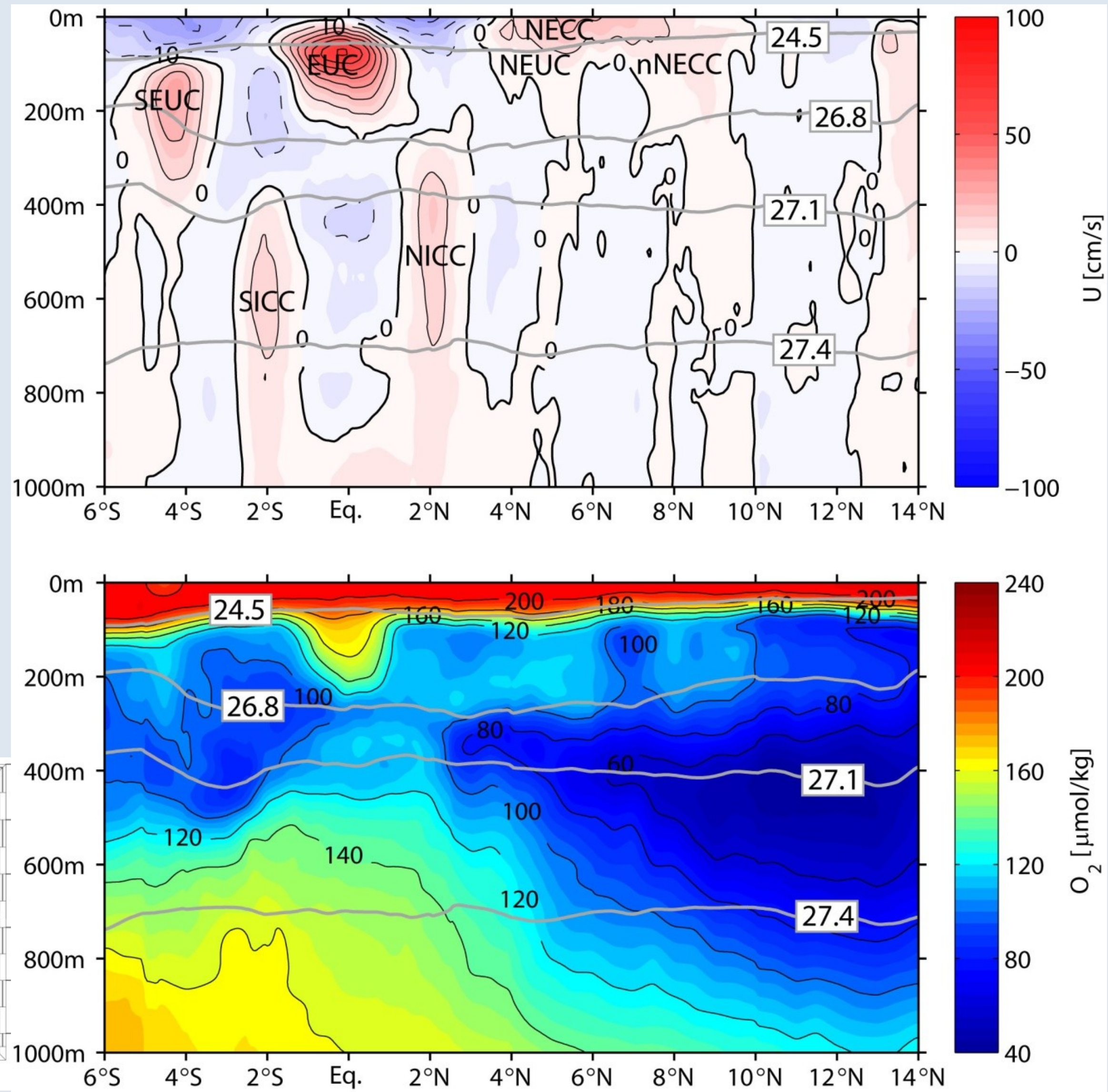
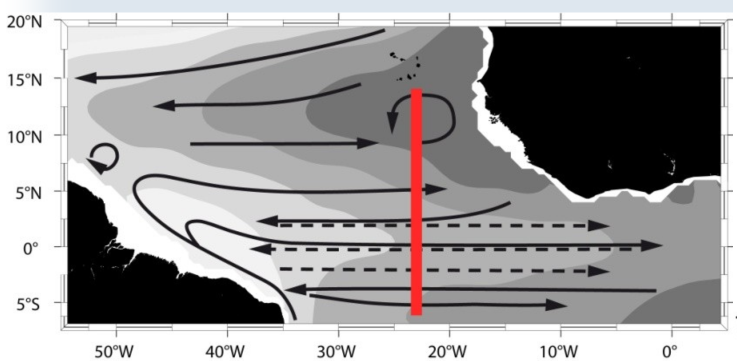
Mean 23°W Section 1999-2008

Vigorous equatorial zonal currents; latitudinally alternating zonal jets in the OMZ

North-South gradient in salinity

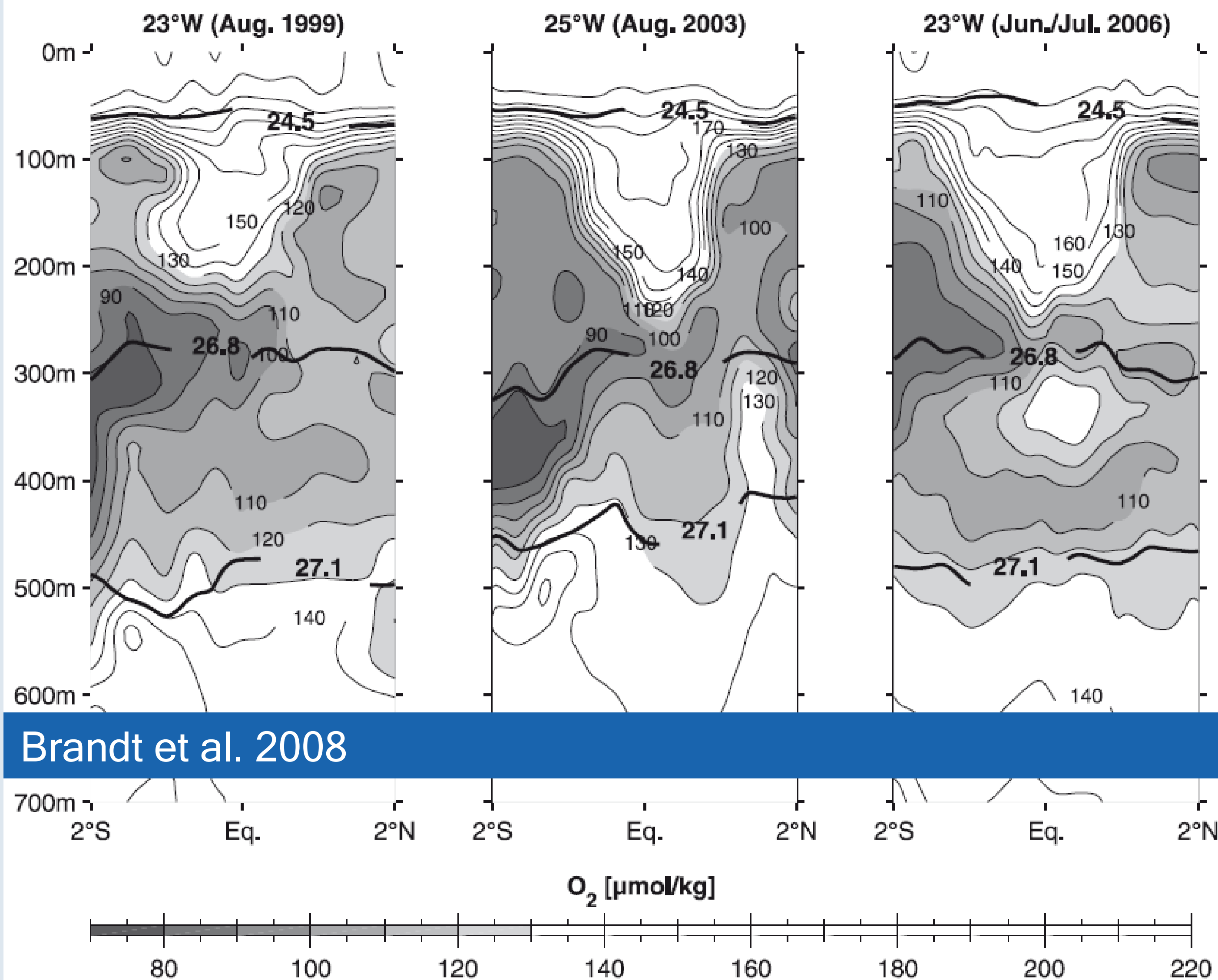
At OMZ core depth oxygen maximum at the equator.





Equatorial Oxygen Distribution

Large interannual variability of the equatorial oxygen distribution: oxygen maxima associated with EUC, NICC, SICC and stacked jets.



Brandt et al. 2008

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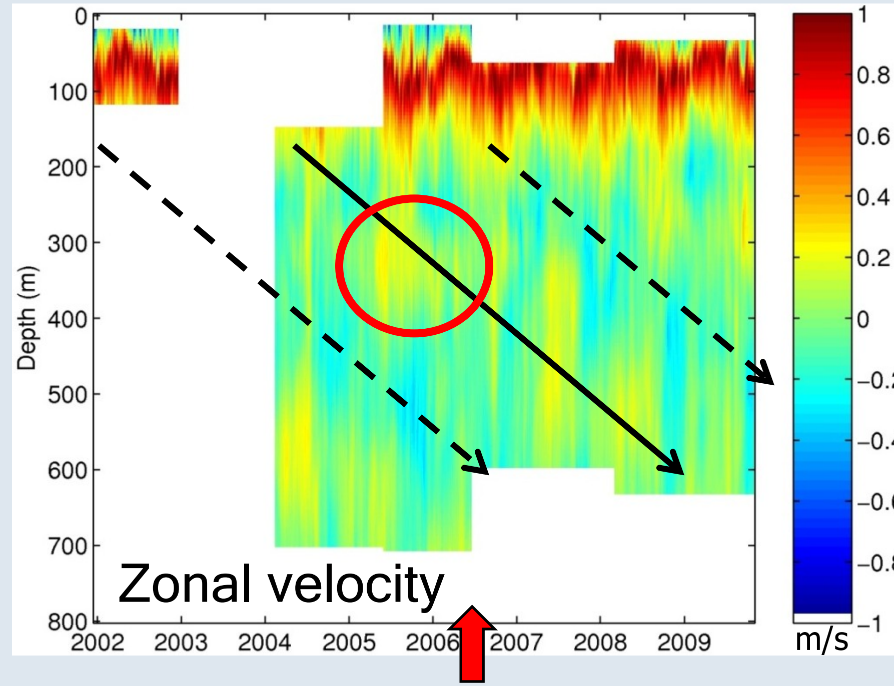
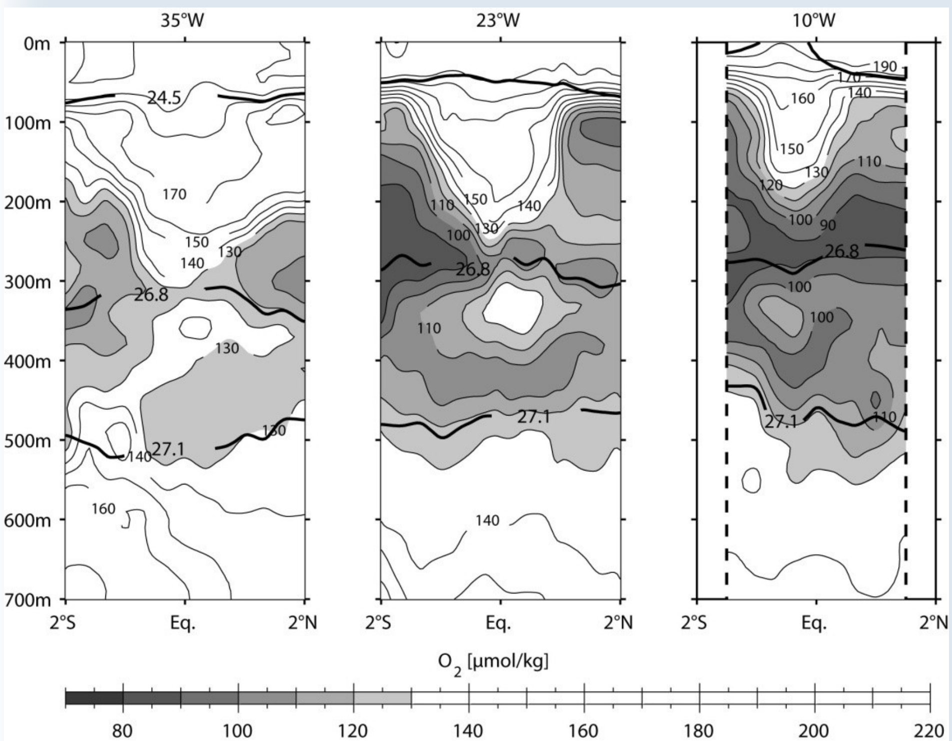
Oxygen Tongues at the Equator

Stacked jets at 23°W with quasi-periodic (4 years) behavior and downward phase propagation.





During phases of eastward flow, generation of oxygen tongues across the whole equatorial Atlantic: ventilation of the equatorial East Atlantic.

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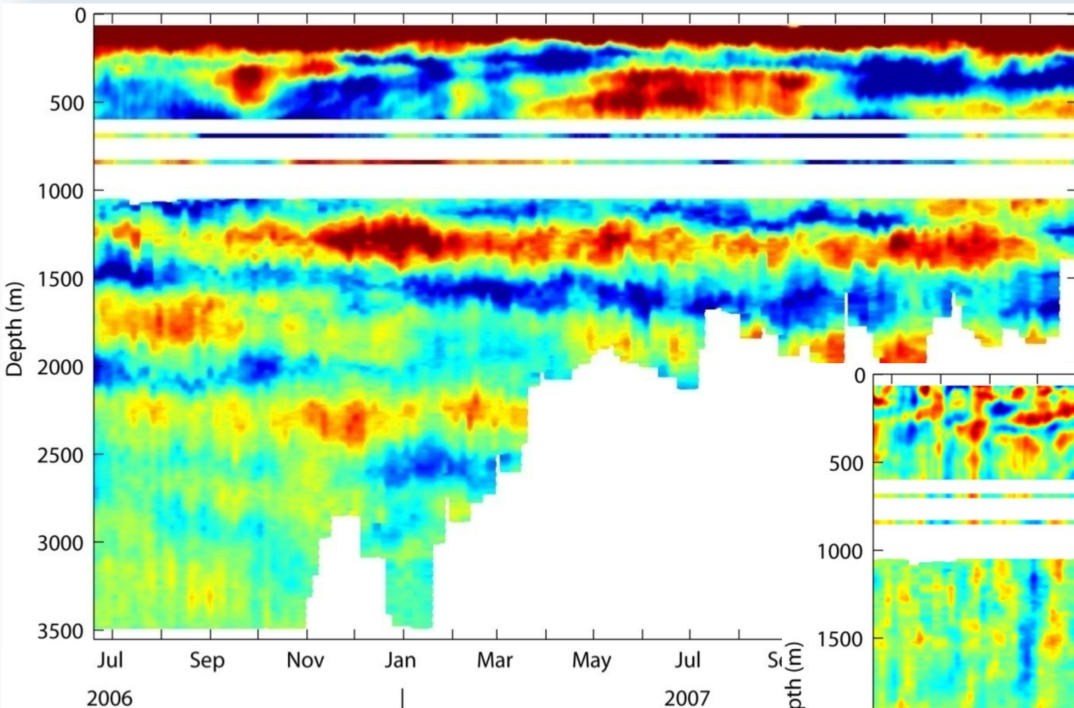
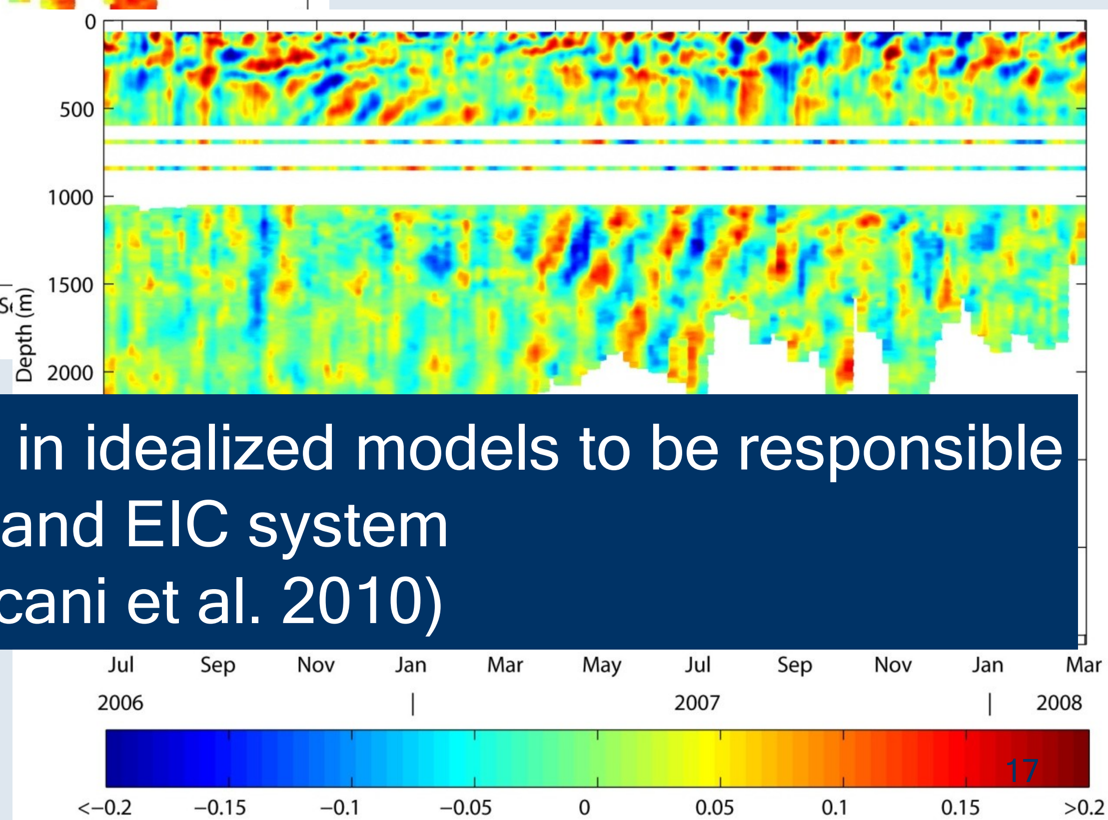
Equatorial Deep Jets



Zonal (left) and meridional (right) velocity [m/s] measured at 23°W, 0°N with ADCP and moored profiler.



Yanai beams are identified in idealized models to be responsible for the generation of EDJs and EIC system (d'Orgeville et al. 2007; Ascani et al. 2010)

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Equatorial Atlantic Ventilation

- Eastward flow within NICC/SICC at 2°N/S
- Stacked jets at the equator superimposed on westward flowing Equatorial Intermediate Current (EIC)
- East- and westward advection results in strong mixing between western boundary regime and eastern equatorial Atlantic

Mean advection together with the occurrence of stacked jets produces a broad oxygen maximum in the equatorial band between 2°S and 2°N.

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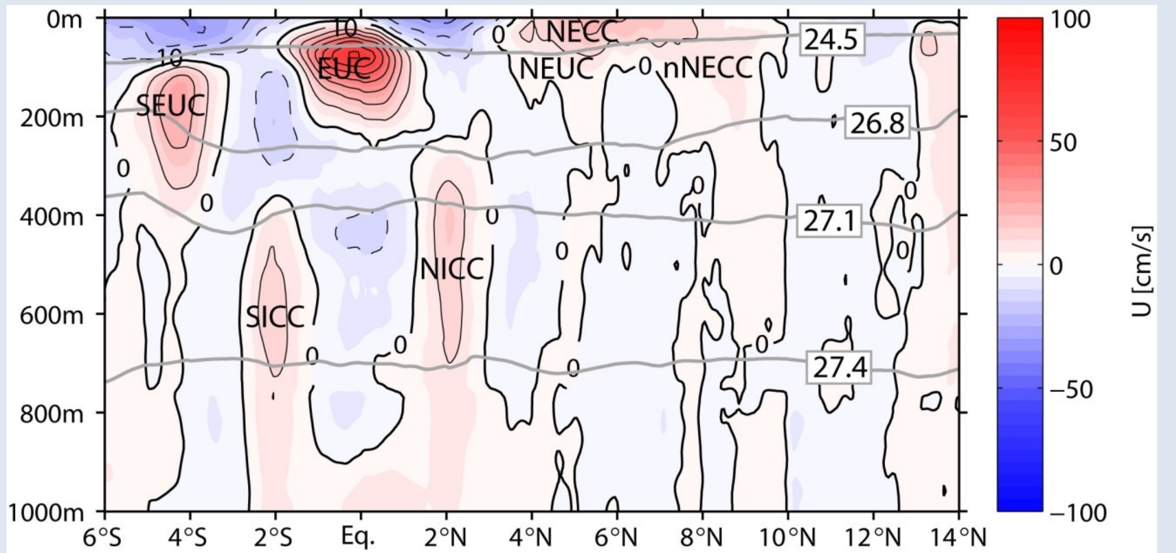
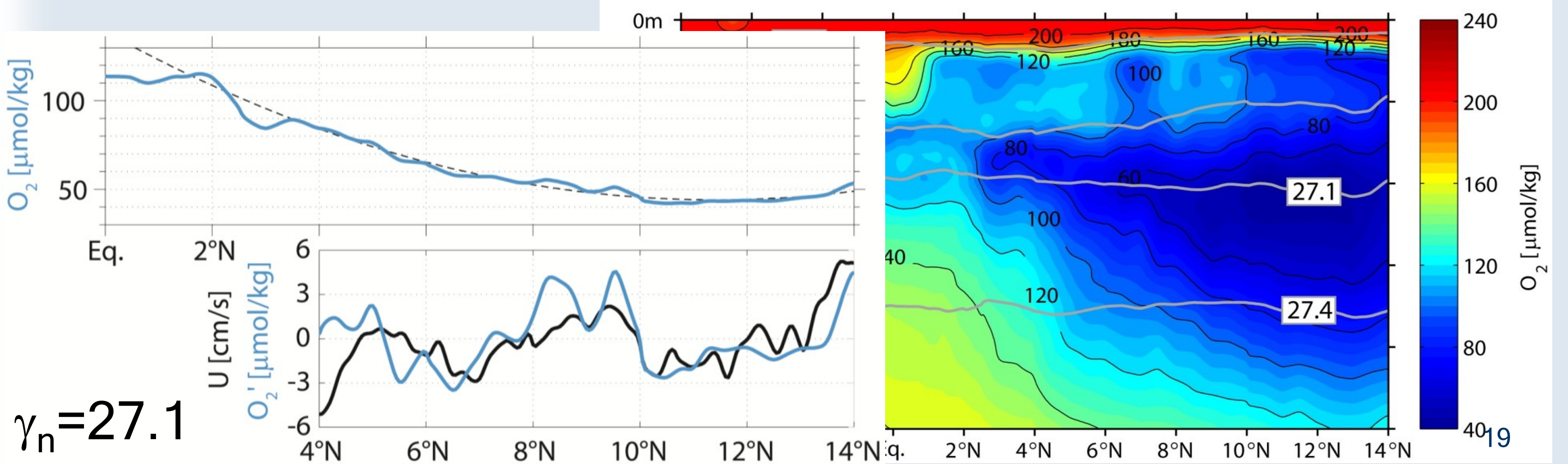
Latitudinally Alternating Zonal Jets in the OMZ

Local oxygen maxima relative to background oxygen curvature at neutral density surface γ_n=27.1 correspond to eastward flow.





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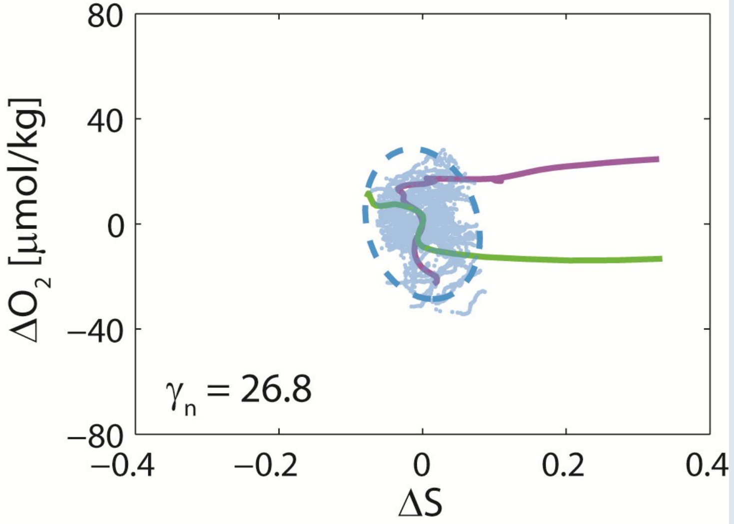
Salinity-Oxygen Scatter

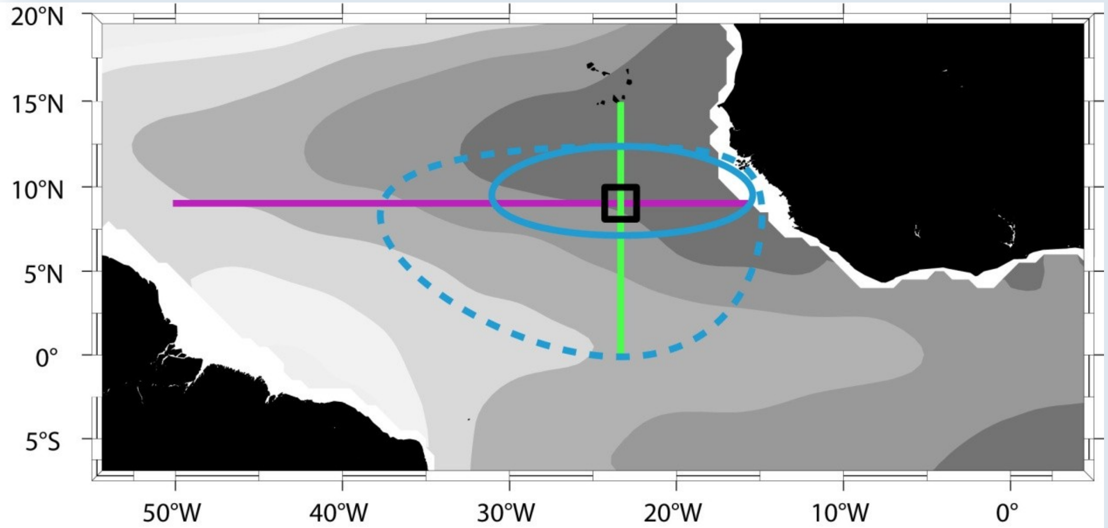
Climatological zonal S-O_2 relation

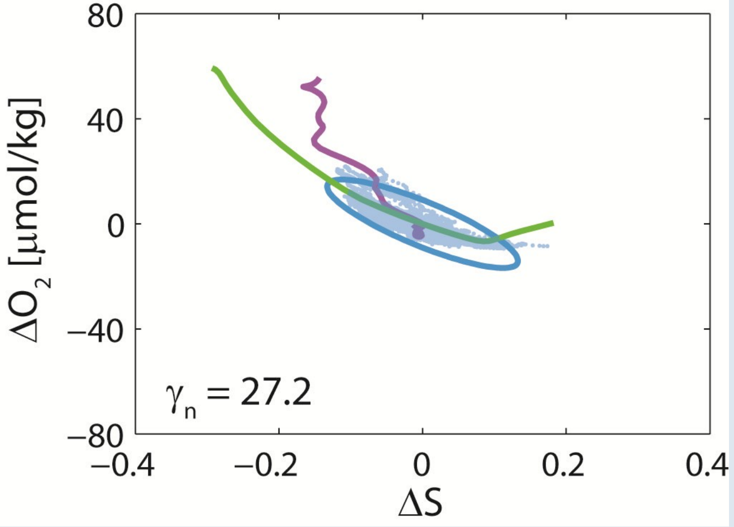
Climatological meridional S-O_2 relation

S-O_2 data from 2° by 2° box

Variance ellipses encompassing 95% of S-O_2 data and resulting meridional and zonal ranges







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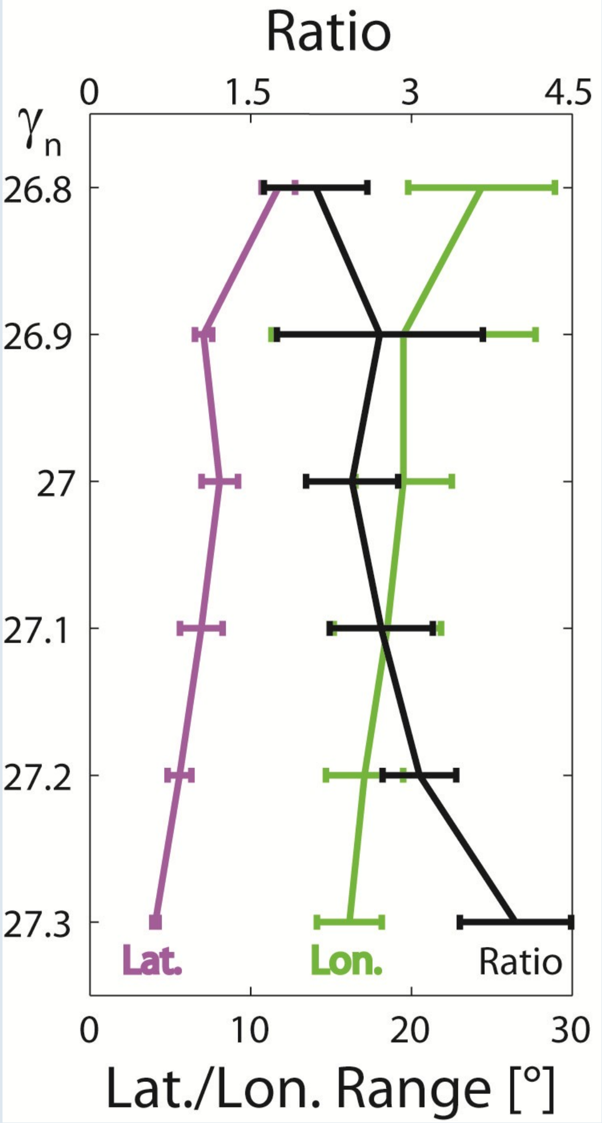
Salinity-Oxygen Scatter

- Larger scatter and larger ranges at shallower density surfaces.
- Ratio between zonal and meridional range increases with depth.
- Effective diffusivity: $k_e \approx c_e U_e L_e$ and for isotropic efficiency factor ratio of zonal and meridional diffusivity:

$k_{ex}/k_{ey} \sim L_{ex}^2/L_{ey}^2$

- Strong zonal-meridional anisotropy with ratio of 5 to 15.
- It includes also the stirring effect of east- and westward jets.



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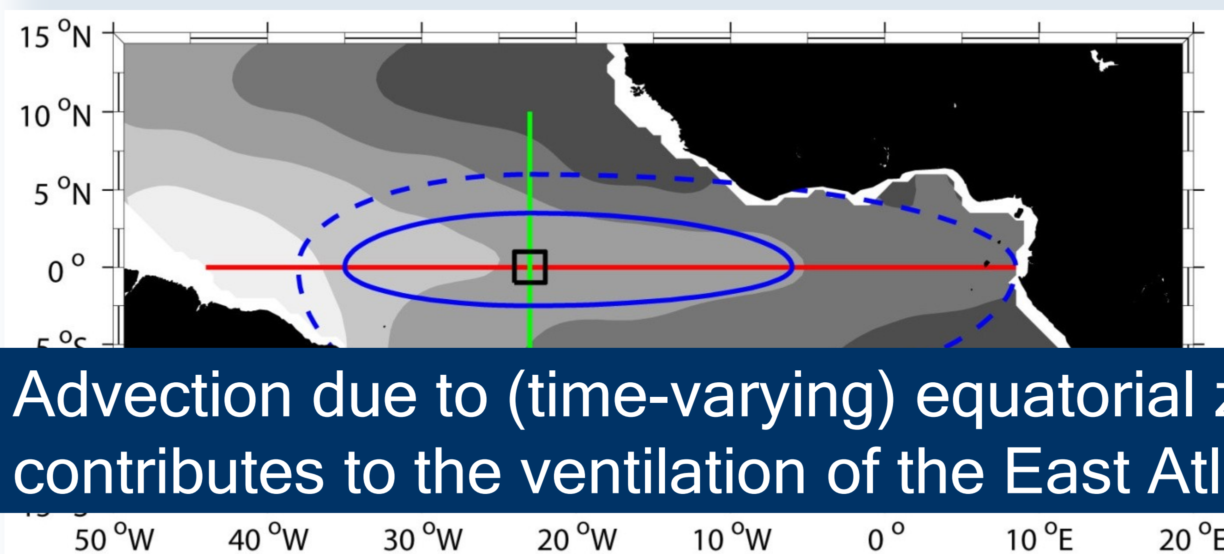
Salinity-Oxygen Scatter

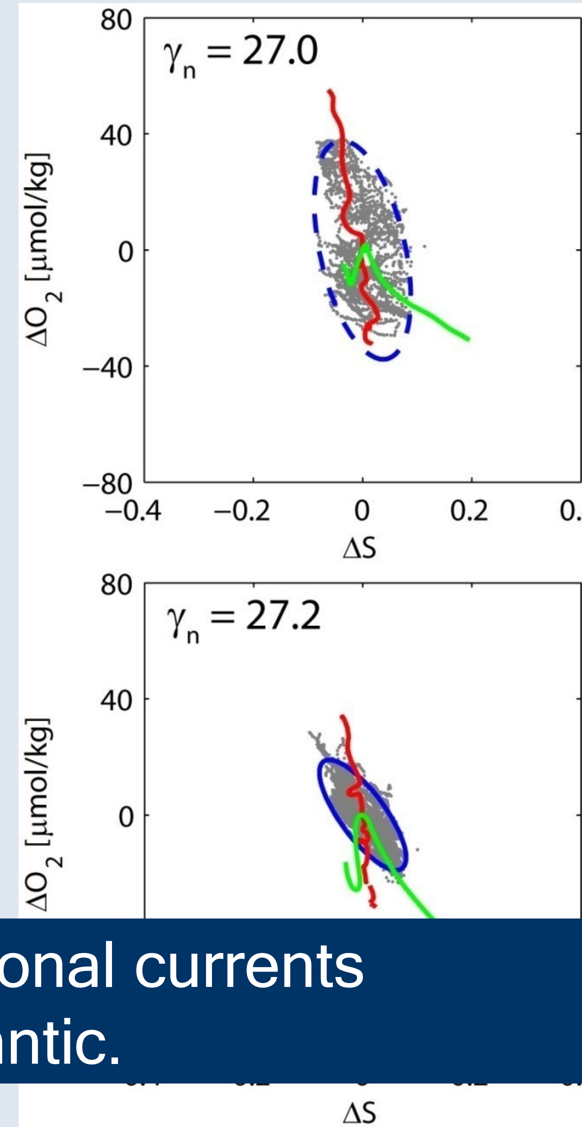
Scatter at the equator is associated with even larger anisotropy.

Ratio of zonal to meridional diffusivity:

8 at shallower and 25 at deeper density surfaces.

Stacked jets contribute to anisotropy.





Advection due to (time-varying) equatorial zonal currents contributes to the ventilation of the East Atlantic.

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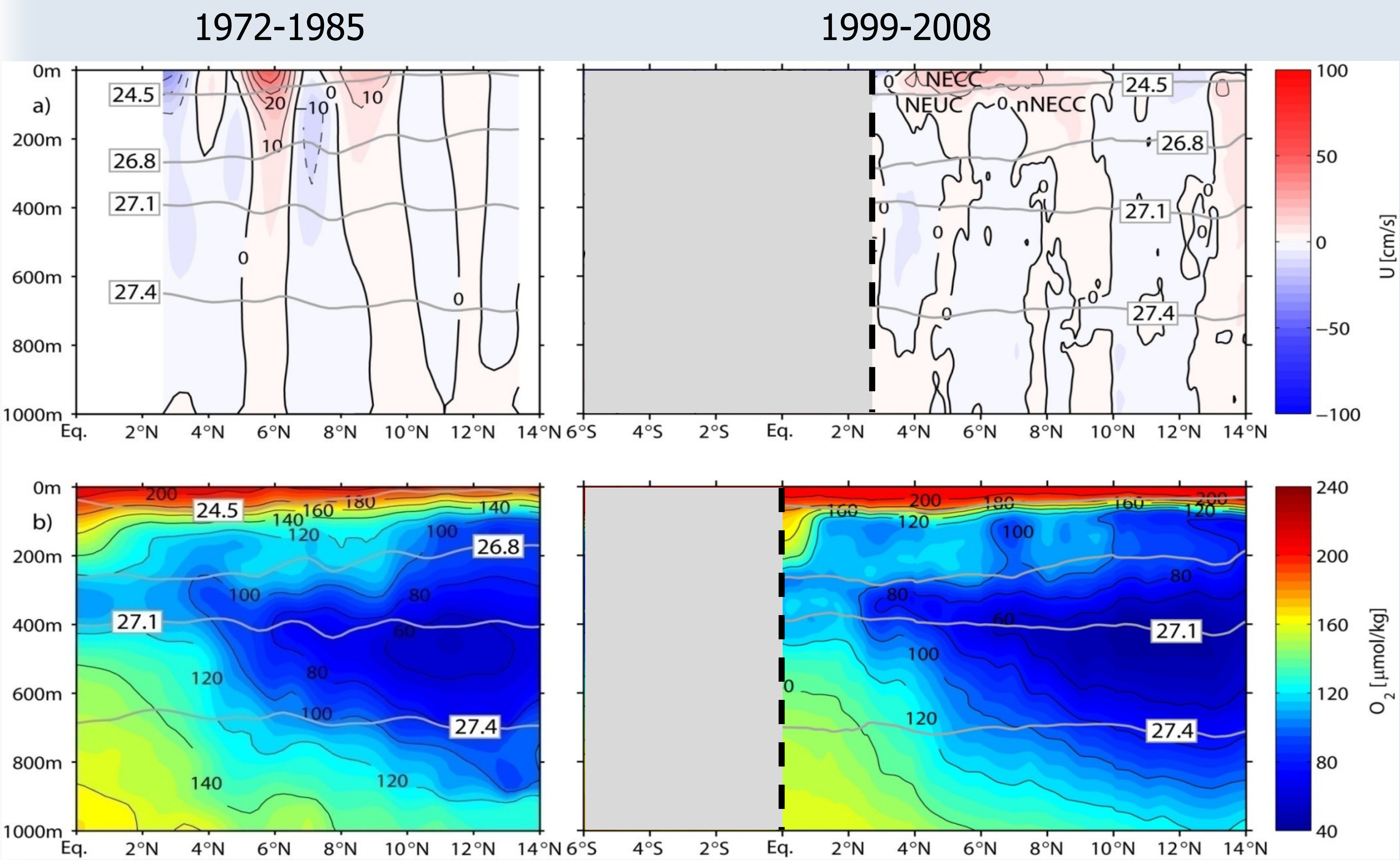
Oxygen and Current Changes along 23°W



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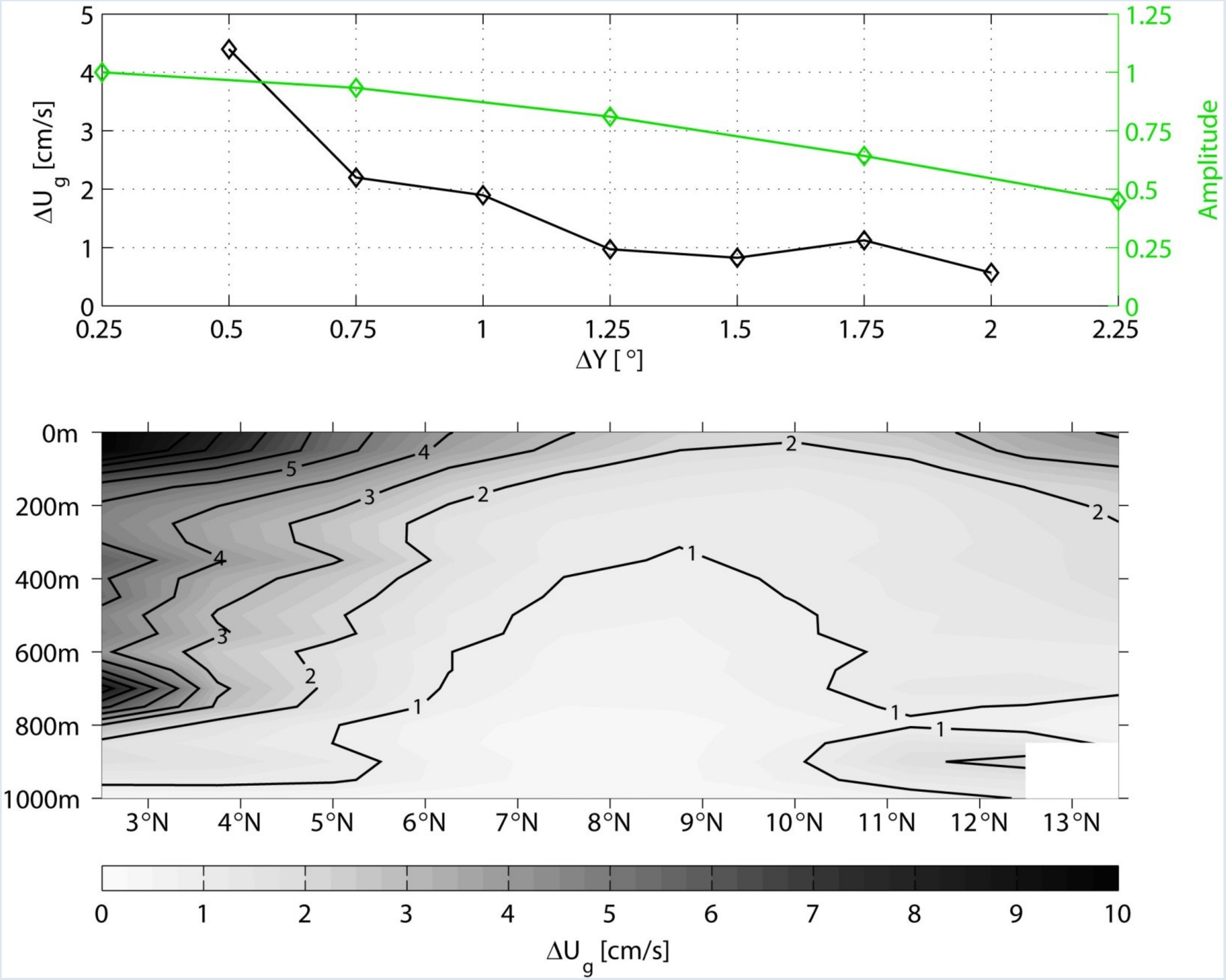
Geostrophic Velocity Error

- Error depends on box size used for averaging geopotential anomalies.
- Larger boxes result in damping of alternating zonal jets.



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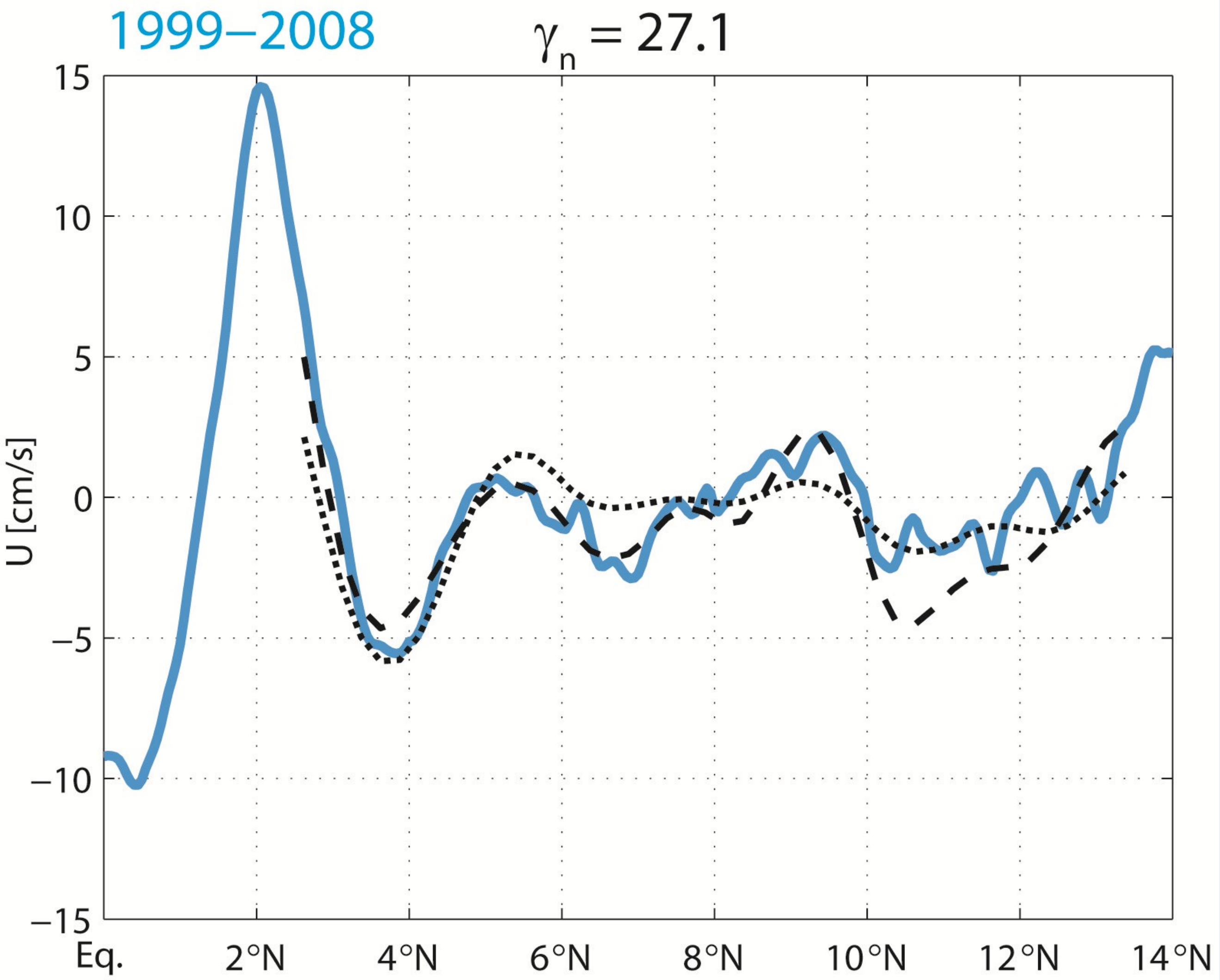
Geostrophic Velocity Error

Direct velocity observations.

Geostrophic velocity rel. to 1000 m.

Geostrophic velocity rel. to abs. velocity at 1000 m.



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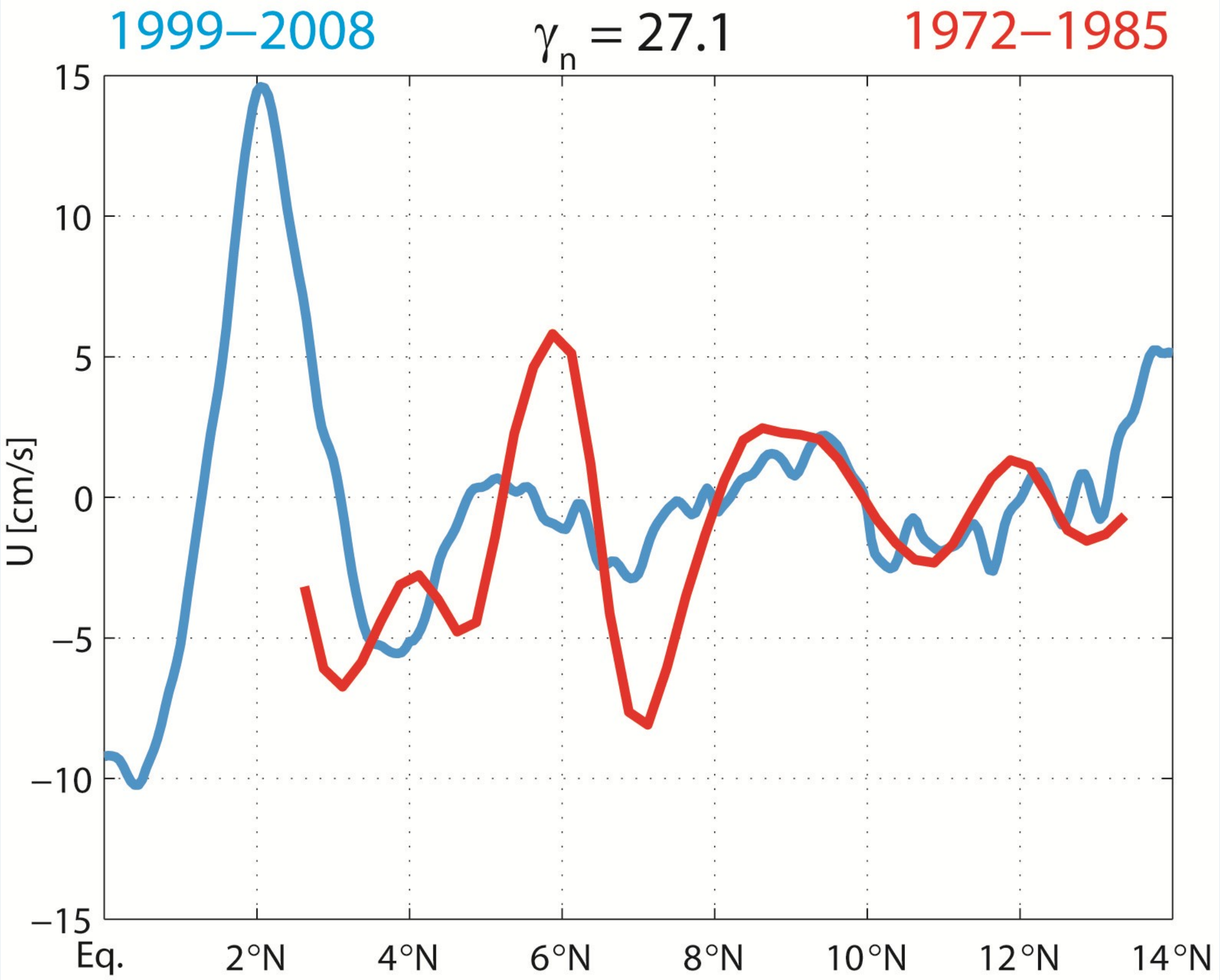
Zonal Velocity Changes

Latitudinally alternating zonal jets with amplitudes of few cm/s in the OMZ were stronger during 1972-1985.



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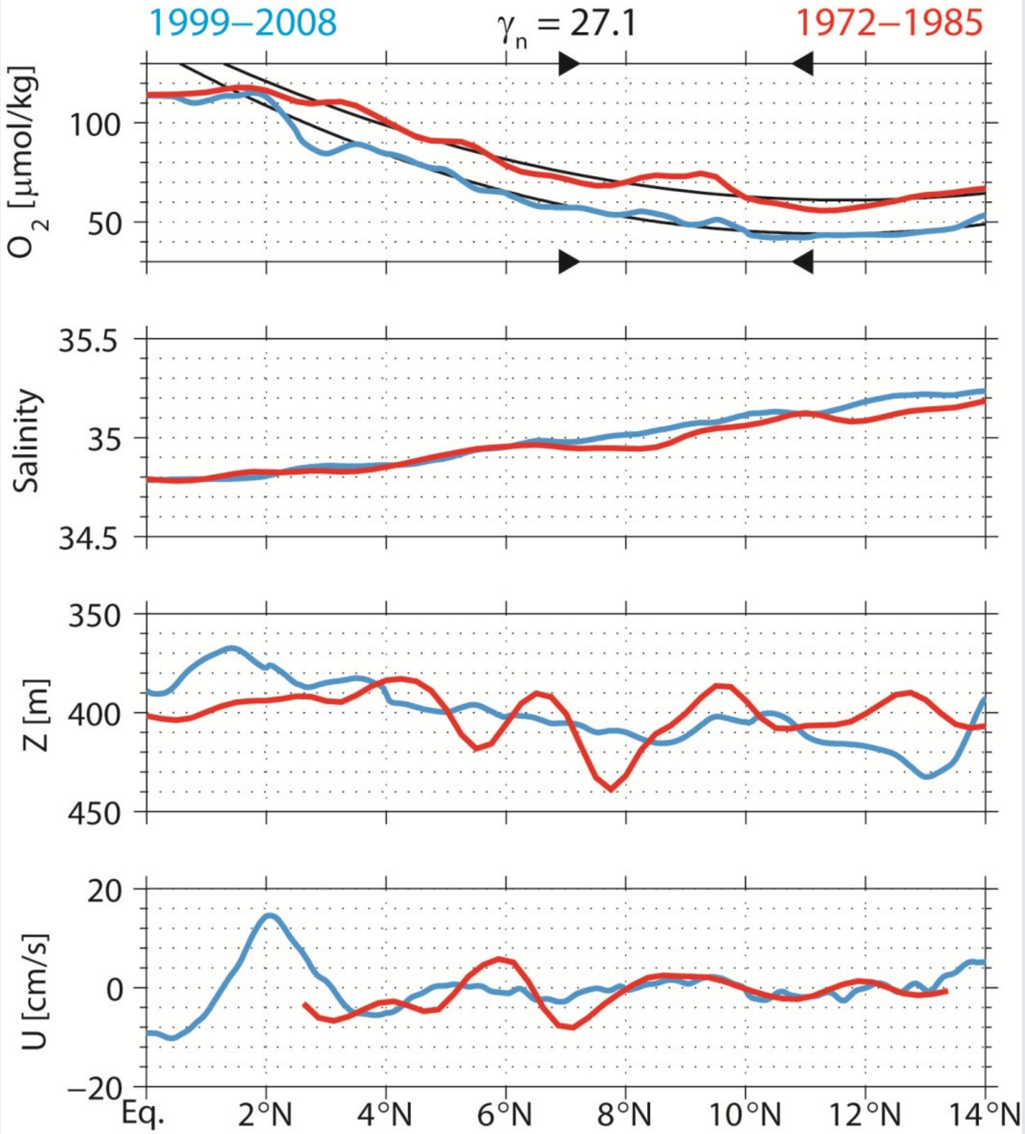
Changes at Neutral Density Surface γ_n=27.1

Oxygen: larger variations in the OMZ during 1972-1985

Salinity: similar gradients, increase in salinity

Depth of density surface: stronger inclinations during 1972-1985

Zonal velocity



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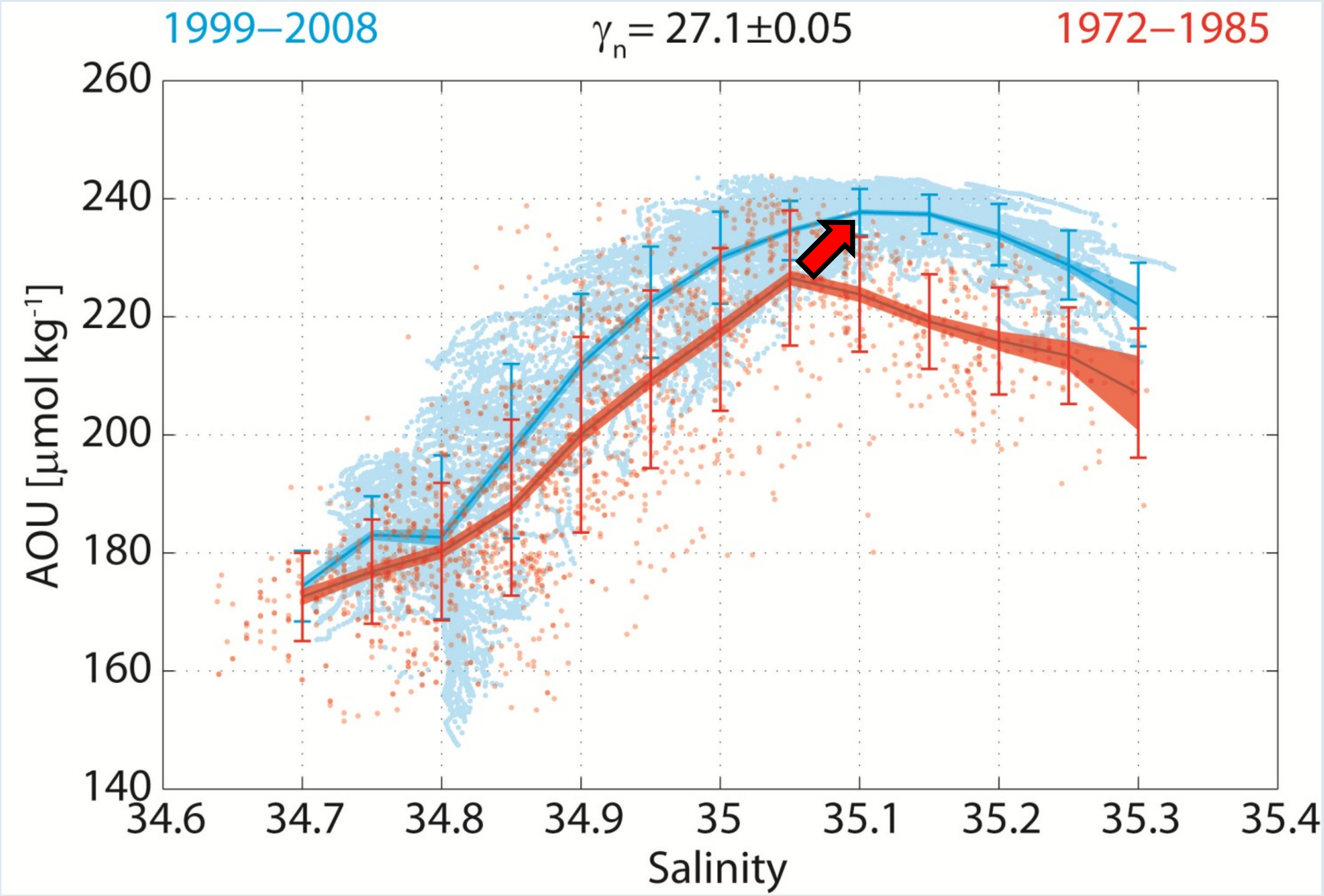
Oxygen changes

Apparent Oxygen Utilization (AOU) along 23°W at the neutral density surface γ_n=27.1 in the core of the OMZ.

Increase in AOU and salinity from 1972-1985 to 1999-2008



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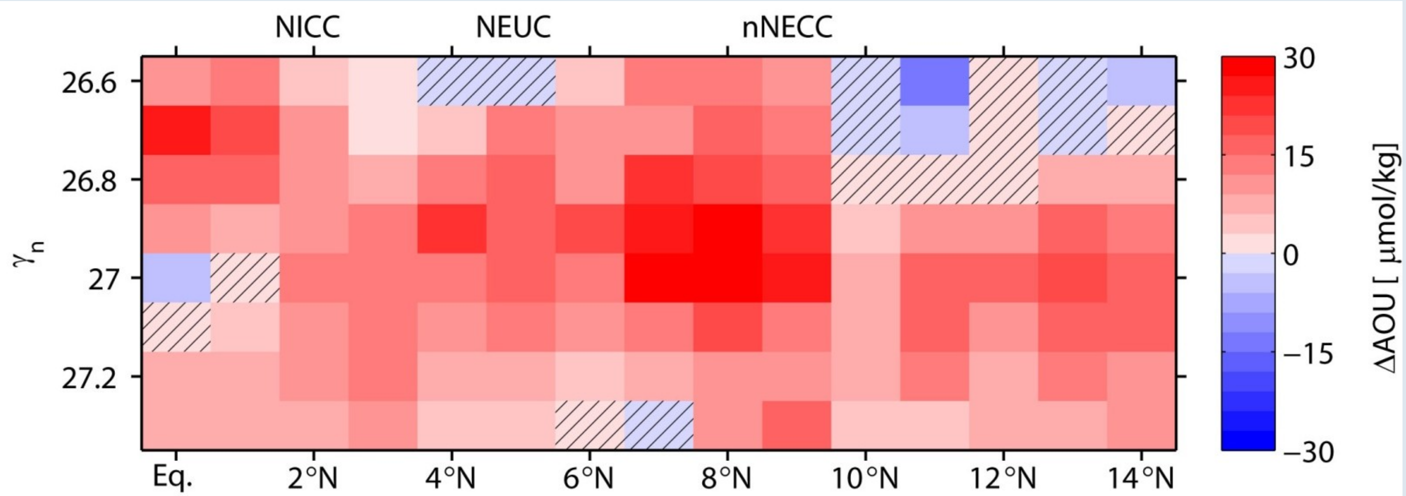
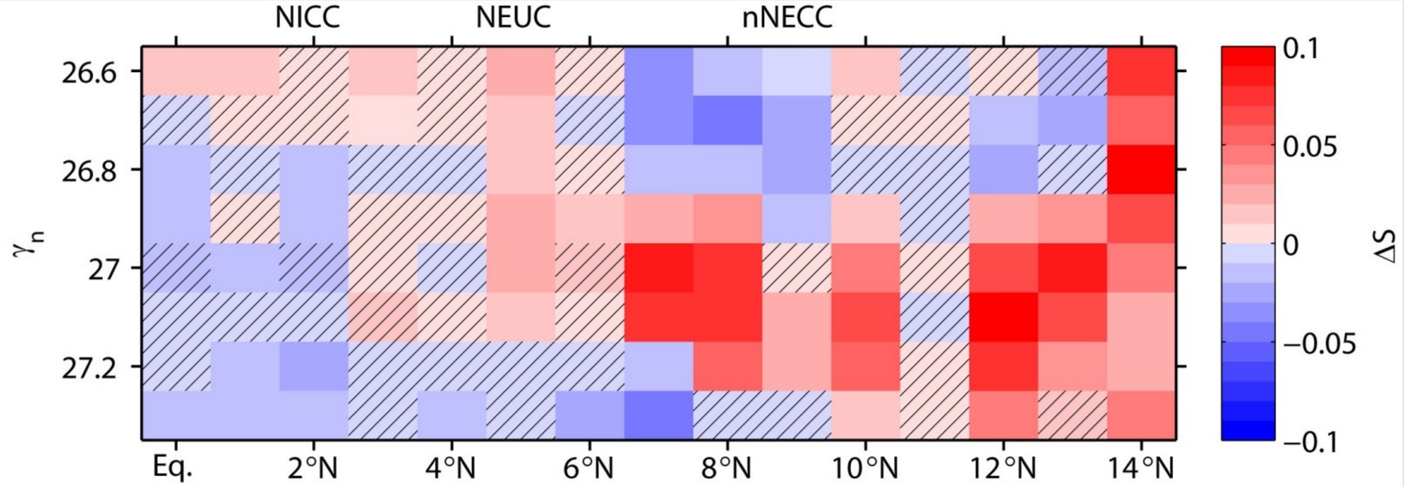
AOU and Salinity Changes

Widespread AOU increase from 1972-1985 to 1999-2008



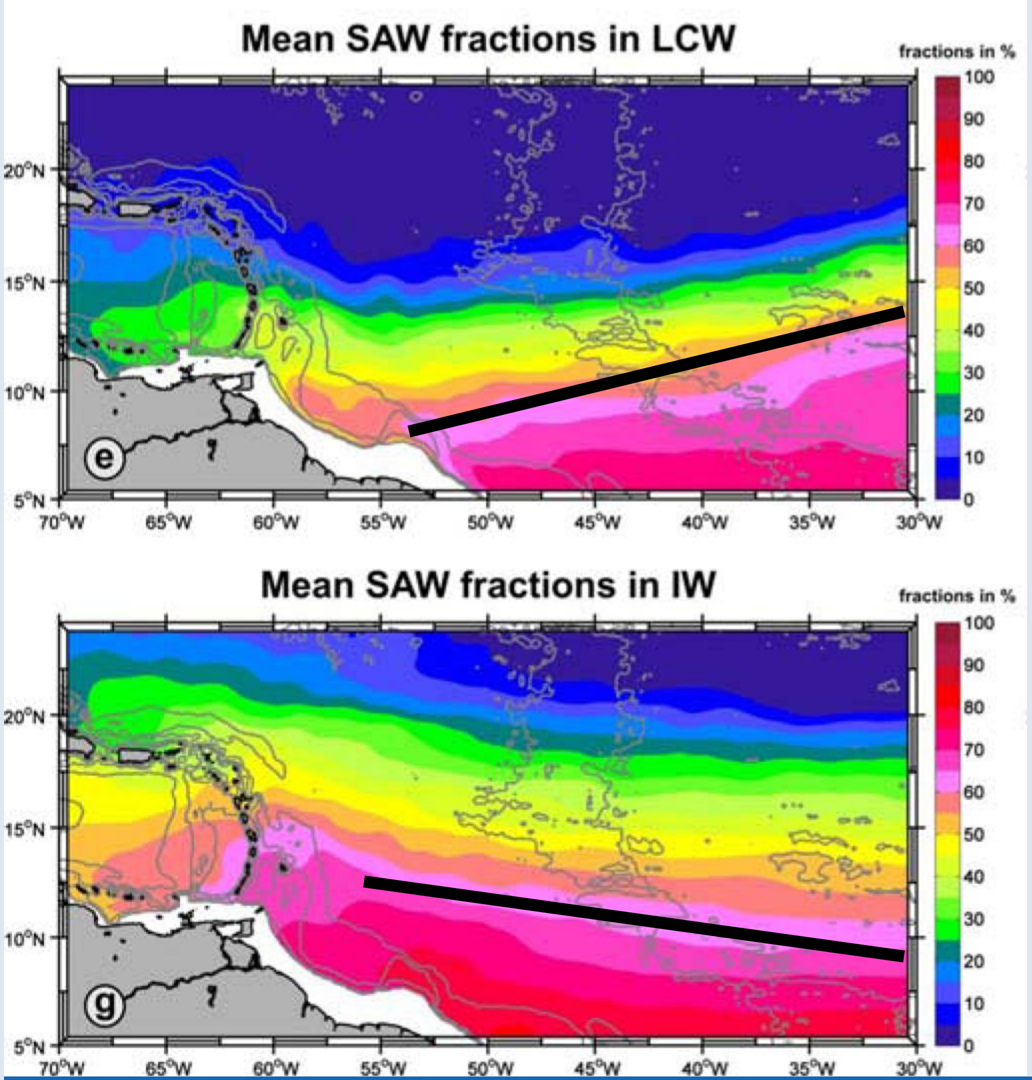
Salinity decrease/ increase in lower Central/ Intermediate Water layer



Changes in AOU and Salinity

Different inclination of the boundary between North and South Atlantic water in the lower Central and Intermediate Water layers.

Observed salinity changes are in agreement with weakening of zonal jet at 9°N.



Kirchner et al. 2009

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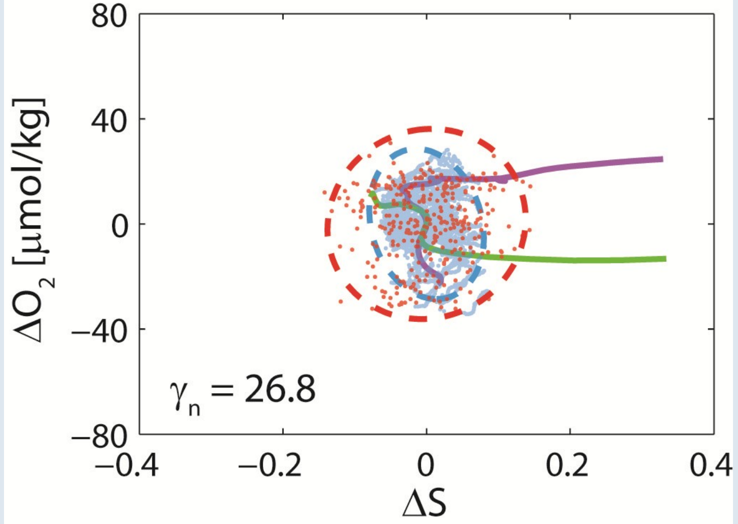
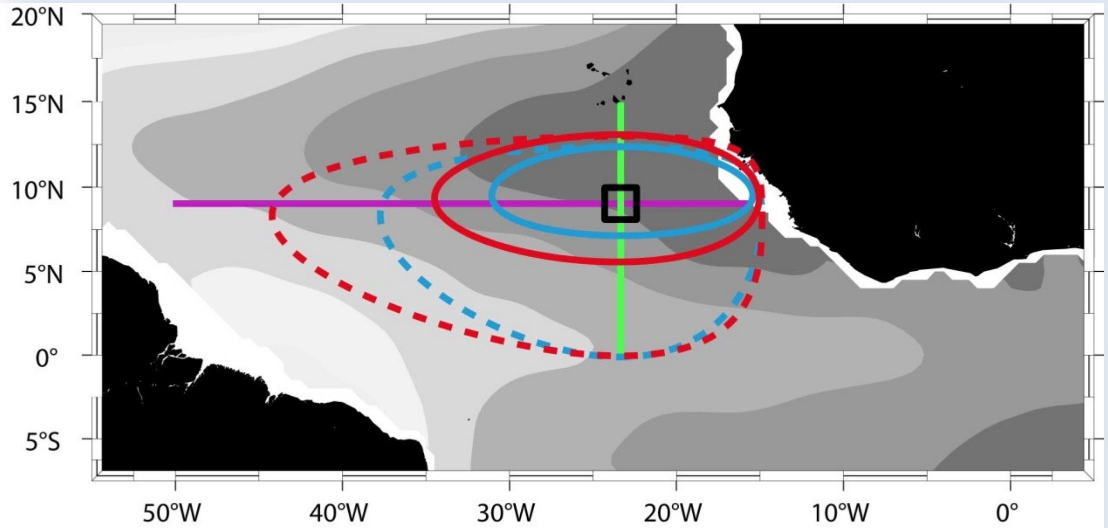
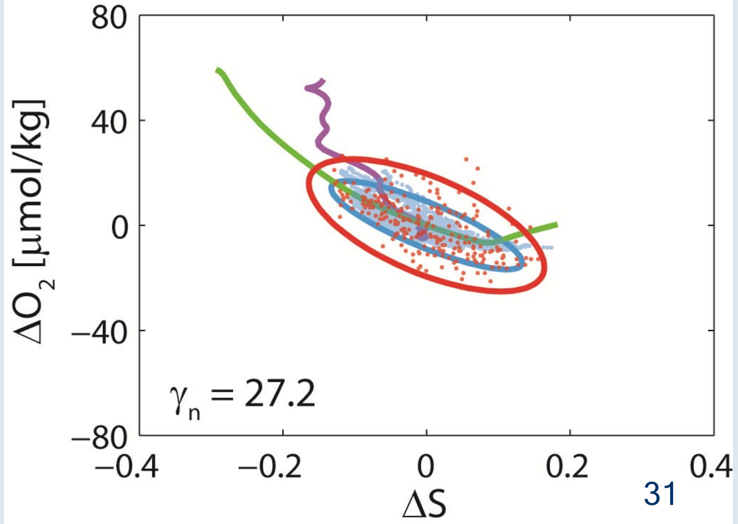
Salinity-Oxygen Scatter Change

Scatter decreased from 1972-1985 to 1999-2008.

Reduced filamentation due to mesoscale eddies and/or zonal jets acting on the background gradients.

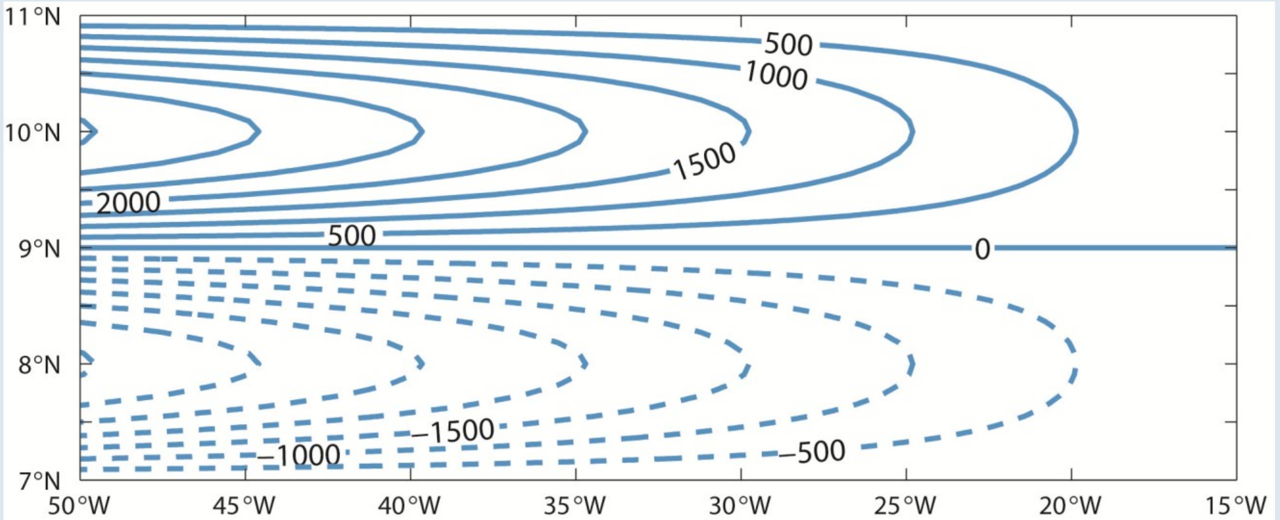


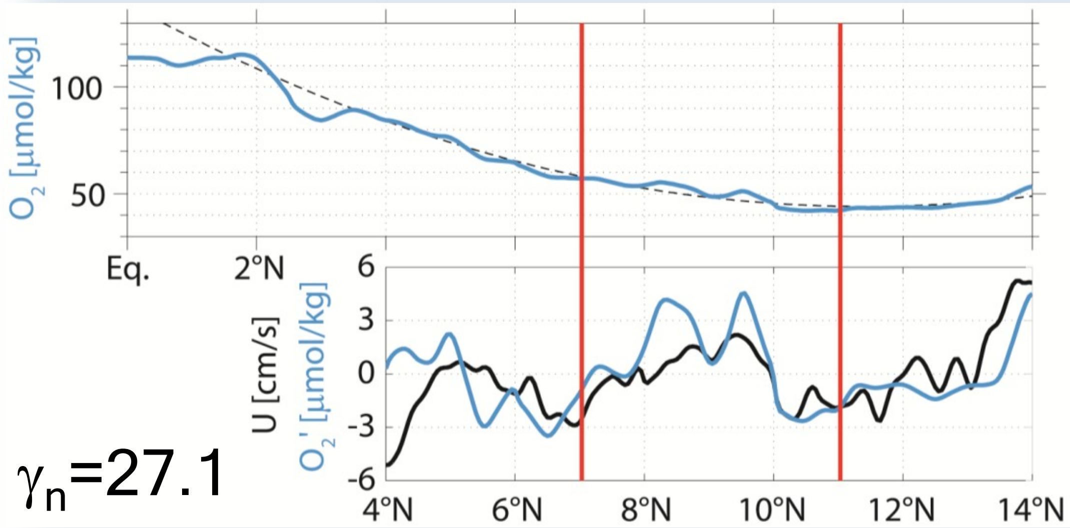




Conceptual OMZ Model

- Model represents a single eastward jet and its westward return flow, superimposed on the background meridional oxygen curvature.



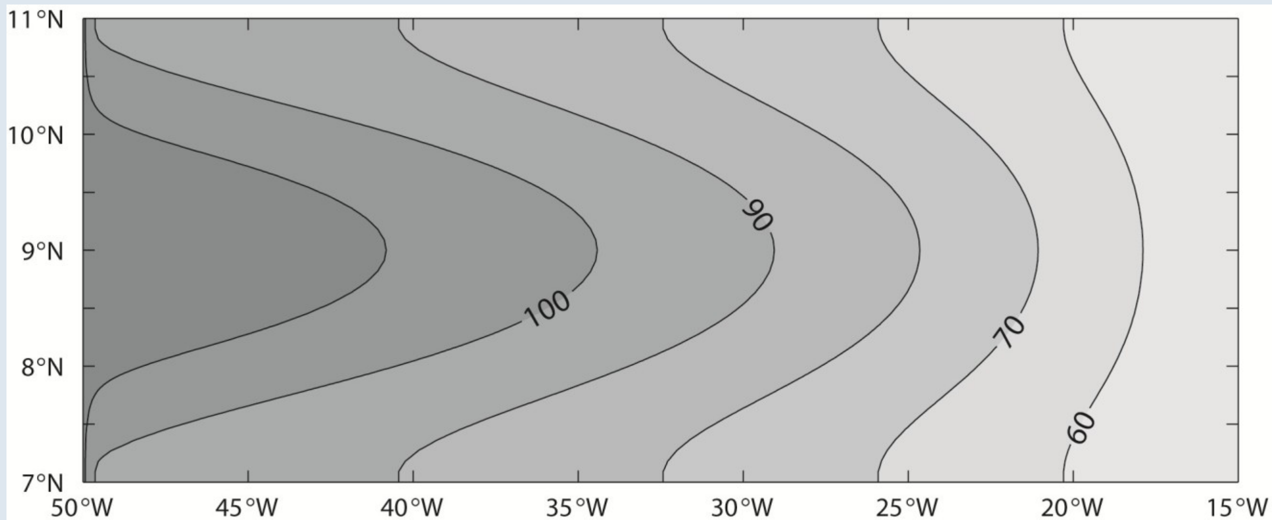


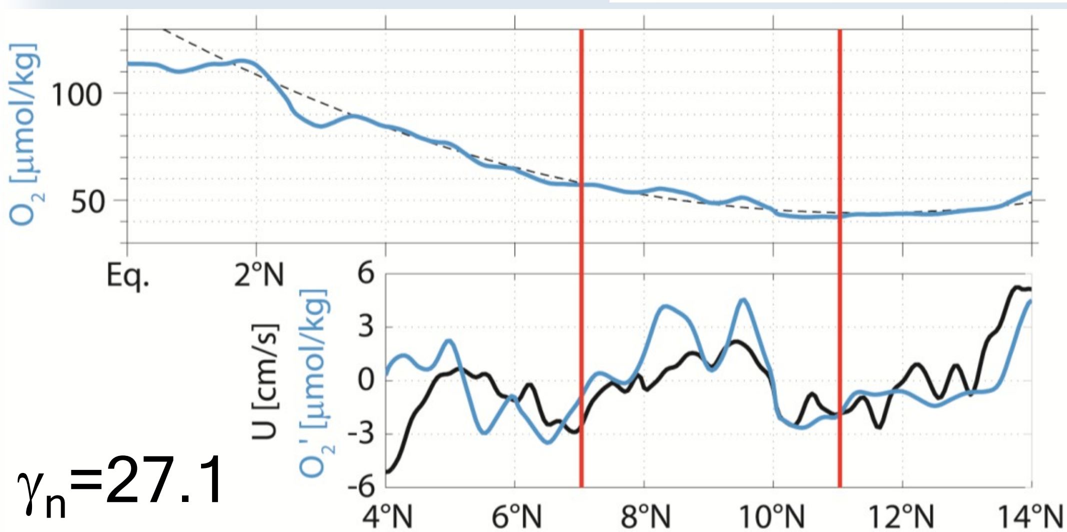
γ_n=27.1

Stream function [m^2/s] defines the constant velocity field.

Conceptual OMZ Model

- Model represents a single eastward jet and its westward return flow, superimposed on the background meridional oxygen curvature.

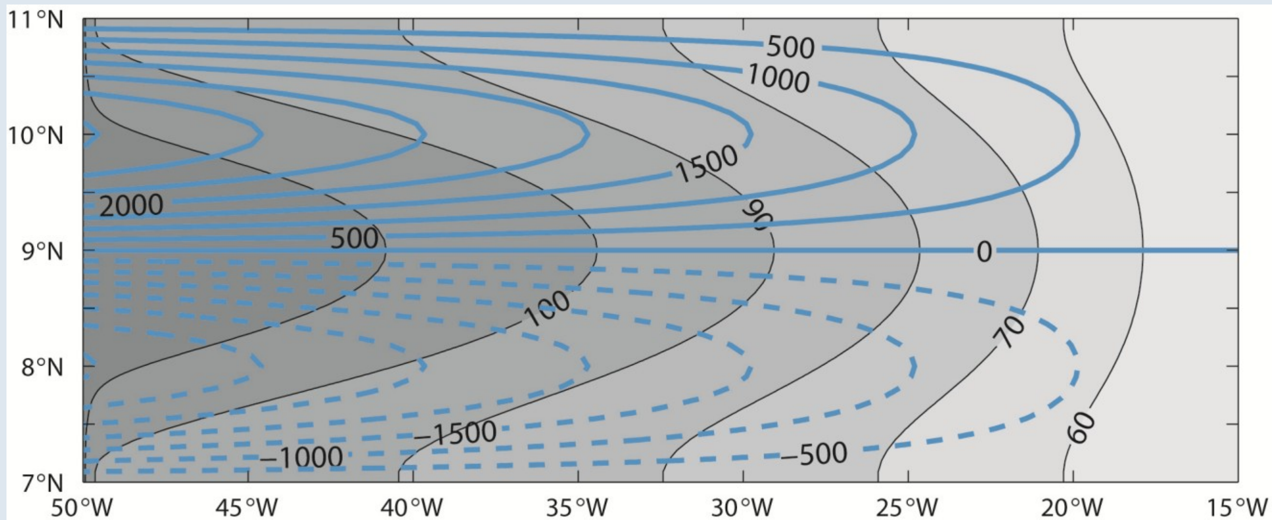


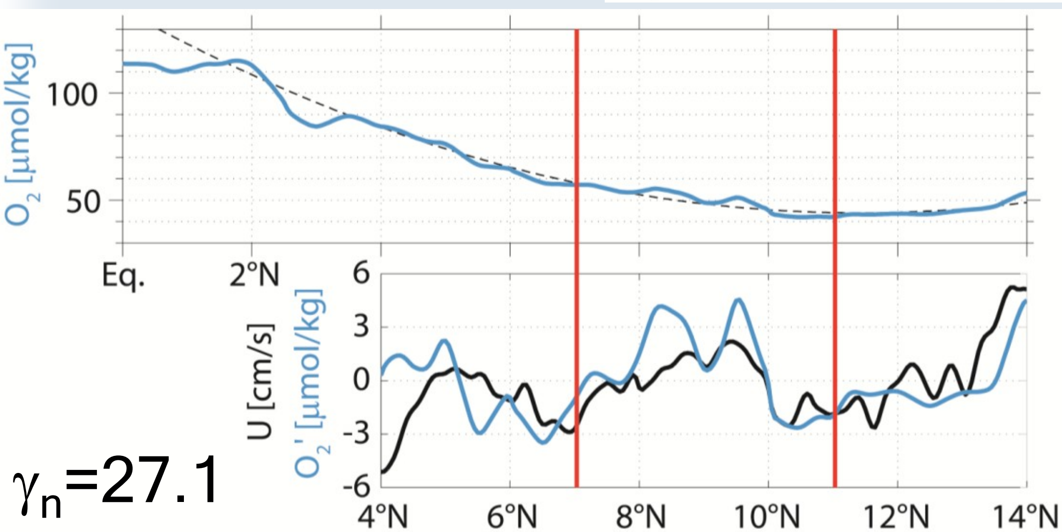


Fixed oxygen concentration at the western boundary.

Conceptual OMZ Model

- Model represents a single eastward jet and its westward return flow, superimposed on the background meridional oxygen curvature.





γ_n=27.1

Model is integrated until equilibrium is reached.

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Conceptual OMZ Model

$$\frac{\partial C}{\partial t} = -JC - u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y} + k_x\frac{\partial^2 C}{\partial x^2} + k_y\frac{\partial^2 C}{\partial y^2} + k_y F_{corr}\frac{\partial^2 C_{bg}}{\partial y^2} + k_z F_{corr}\frac{\partial^2 C_{bg}}{\partial z^2}$$

Oxygen tendency is balanced by

- Consumption
- Zonal and meridional advection associated with mean flow
- Zonal eddy diffusivity
- Meridional eddy diffusivity associated with oxygen anomaly relative to the background oxygen distribution
- Meridional and vertical eddy diffusivity associated with the background oxygen curvature

$J = 0.04\ a^{-1}$, $k_x = 500\ m/s^2$, $k_y = 200\ m/s^2$, $k_z = 10^{-5}\ m/s^2$

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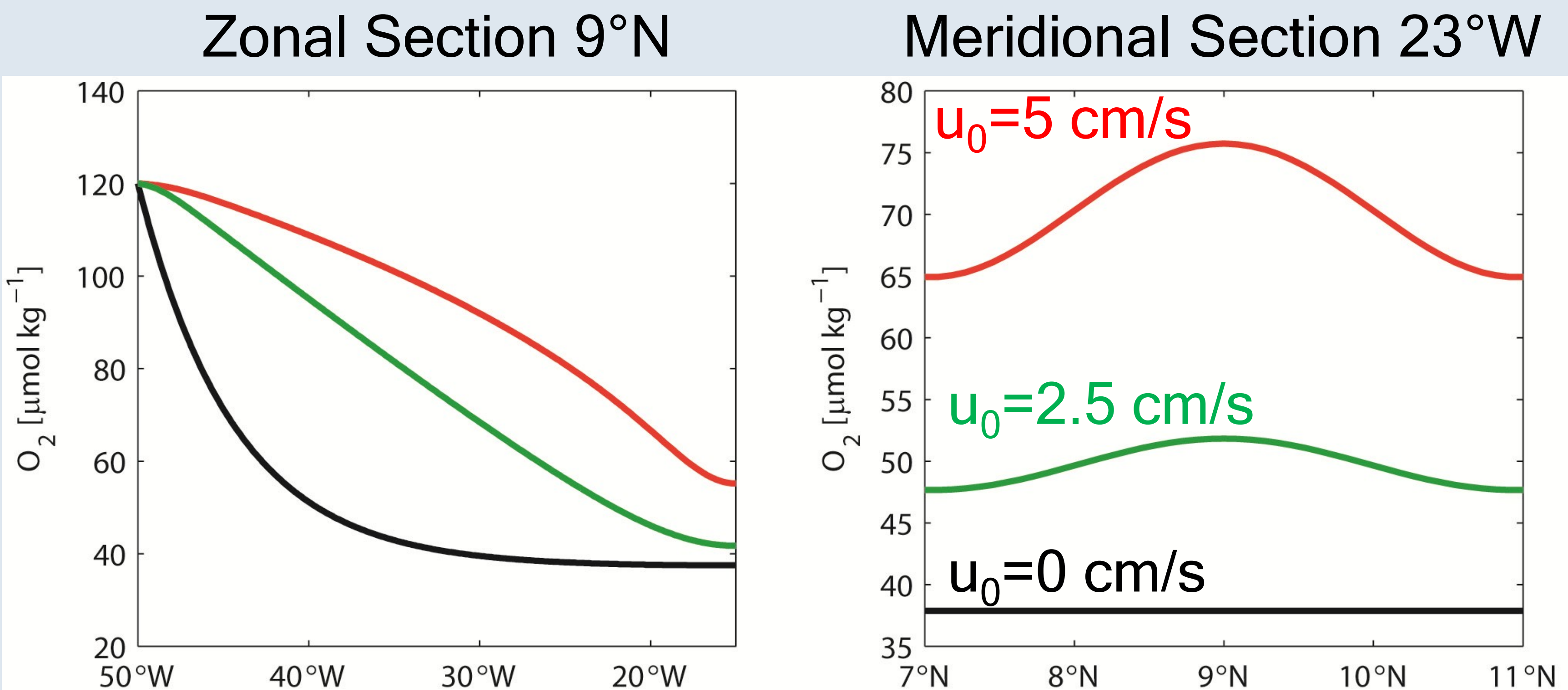
Conceptual OMZ Model

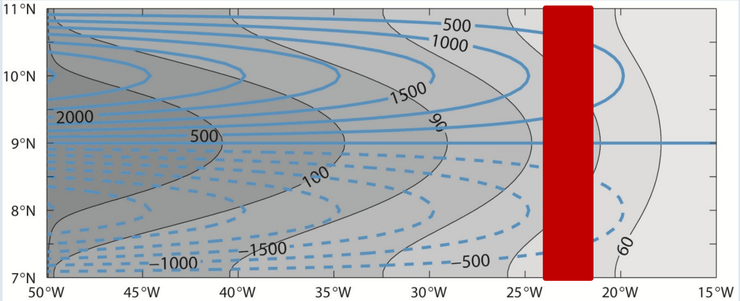


Existence of zonal jets leads to higher oxygen concentrations in the OMZ. Amplitude of the oxygen undulations along 23°W reduces with decreasing jet strengths.

Conceptual OMZ Model

$$\frac{\partial C}{\partial t} = -JC - u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y} + k_x\frac{\partial^2 C}{\partial x^2} + k_y\frac{\partial^2 C}{\partial y^2} + k_y F_{corr}\frac{\partial^2 C_{bg}}{\partial y^2} + k_z F_{corr}\frac{\partial^2 C_{bg}}{\partial z^2}$$

Relative contribution to the oxygen balance [%]
(consumption = -100%)



u_0 = 5 cm/s	33	39	-4	0	19	13
u_0 = 2.5 cm/s	18	11	7	0	37	26
u_0 = 0 cm/s	0	0	2	0	57	41

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Summary (1)

Tropical North Atlantic OMZ is characterized by

- Oxygen minimum levels less than 40 μmol kg^{-1}
- High oxygen levels at the equator due to strong zonal exchange via NICC/SICC and stacked jets
- Ventilation due to lateral eddy fluxes, mean advection, and diapycnal fluxes

Mean advection is due to latitudinally alternating zonal jets with amplitudes of a few cm s^{-1} in the core of the OMZ
⇨ identifiable as local oxygen maxima

Summary (2)

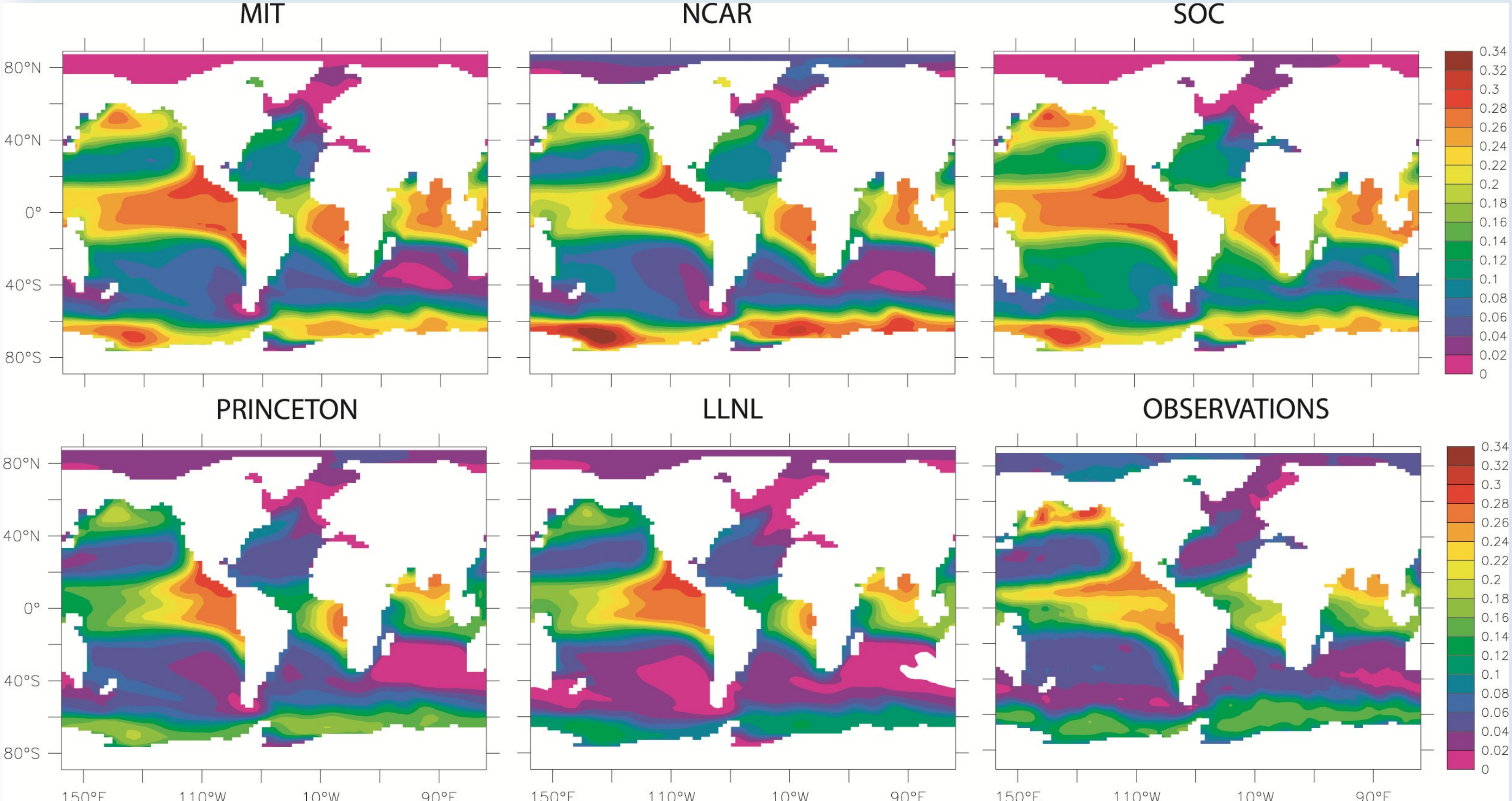
Changes in hydrography and currents of the OMZ along 23°W from 1972-1985 to 1999-2008:

- Oxygen decrease of about 15 μmol kg^{-1} in its core
- Salinity decrease / increase in the central / intermediate water layers consistent with reduced ventilation from the western boundary
- Reduced salinity-oxygen scatter

Weakening of latitudinally alternating zonal jets contributes to the observed oxygen depletion in the North Atlantic OMZ

Discussion: Model Simulations

Annual mean AOU [mol/m^3] in different global models and observations

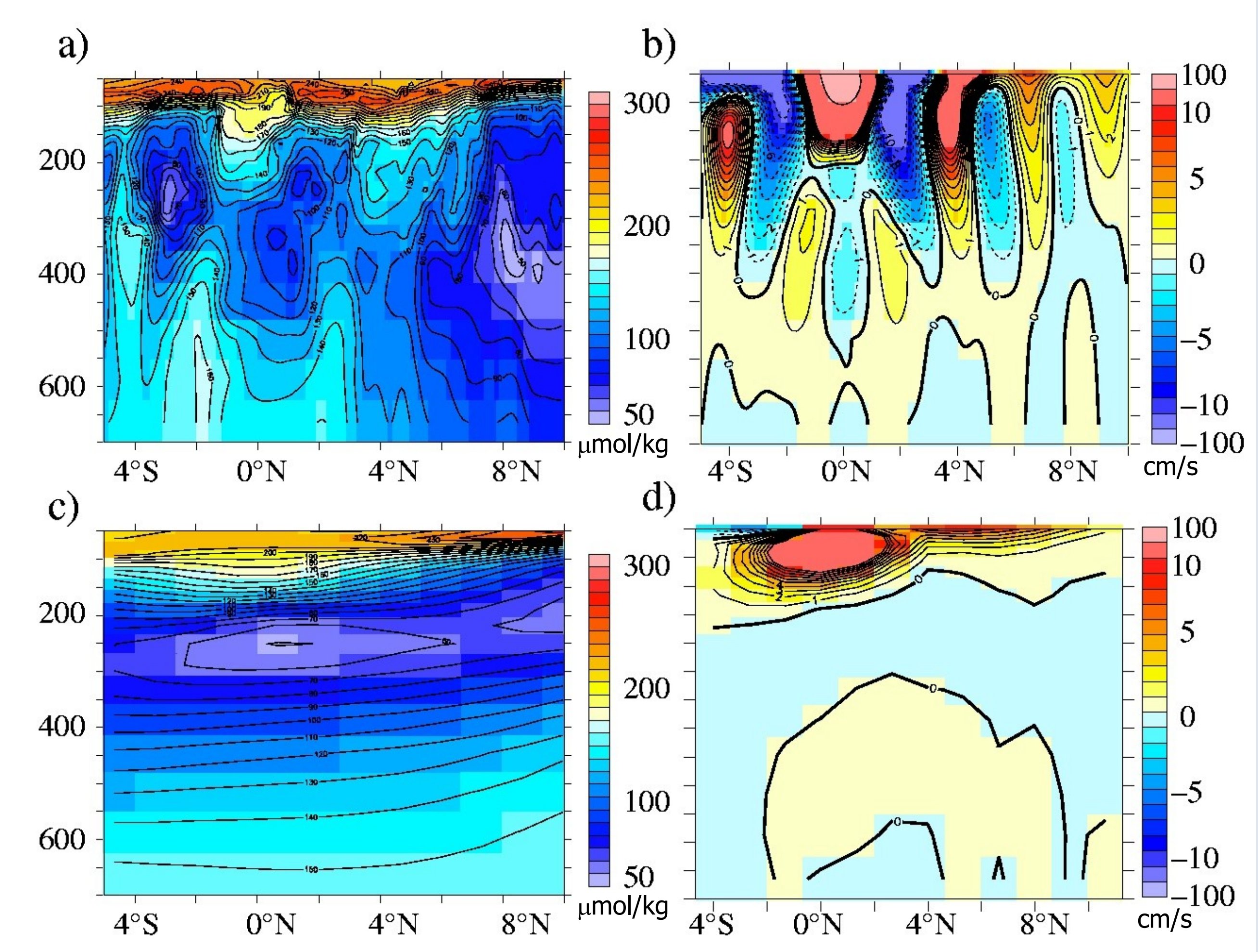


Meissner et al. 2005

Discussion: Model Simulations

High-resolution FLAME model is able to reproduce main current and oxygen structure.

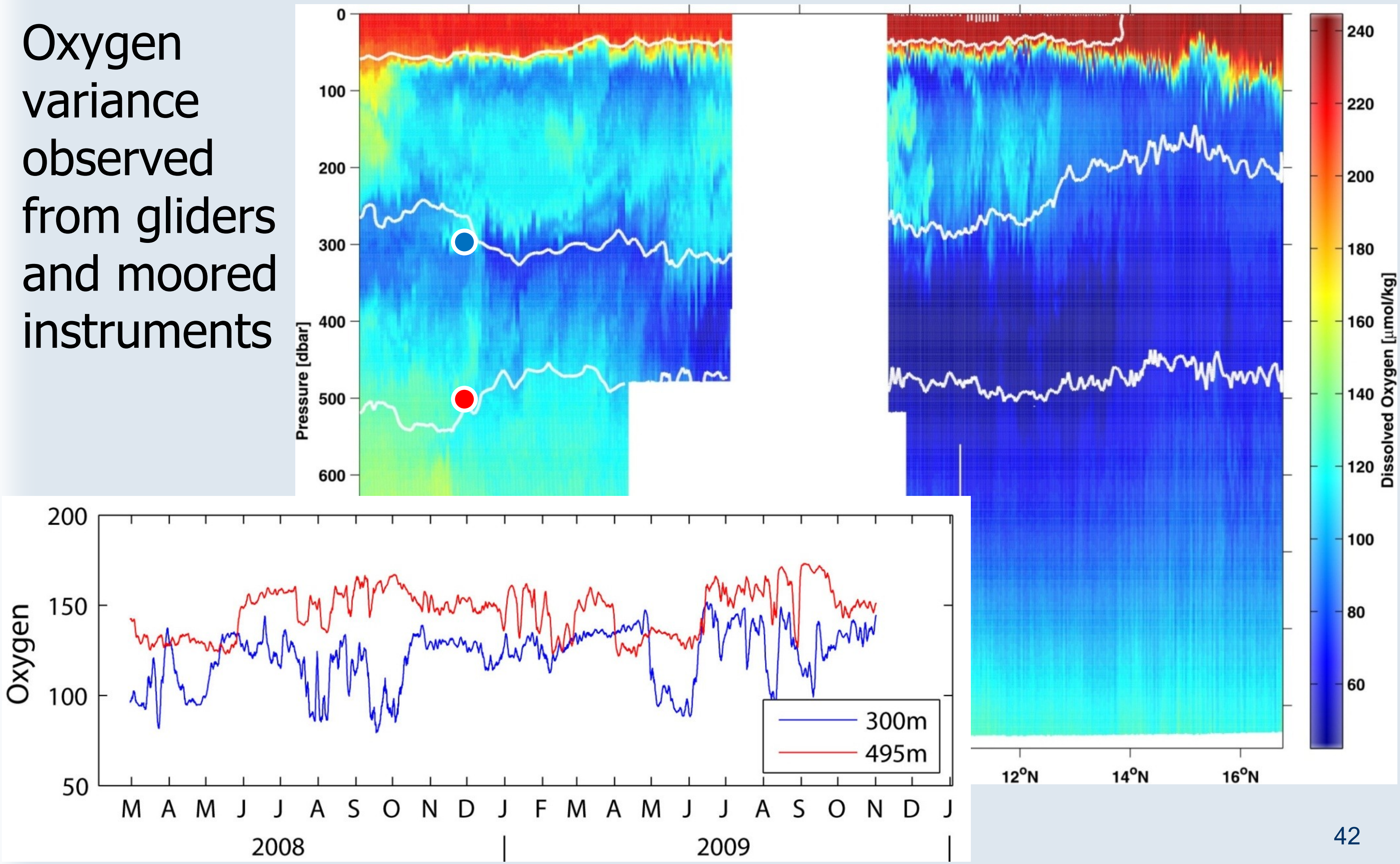
Intermediate currents are still too weak.



1/12° (a,b) and 1/4° (c,d) FLAME simulations, C. Eden

Outlook: Observations at high spatial and temporal resolution

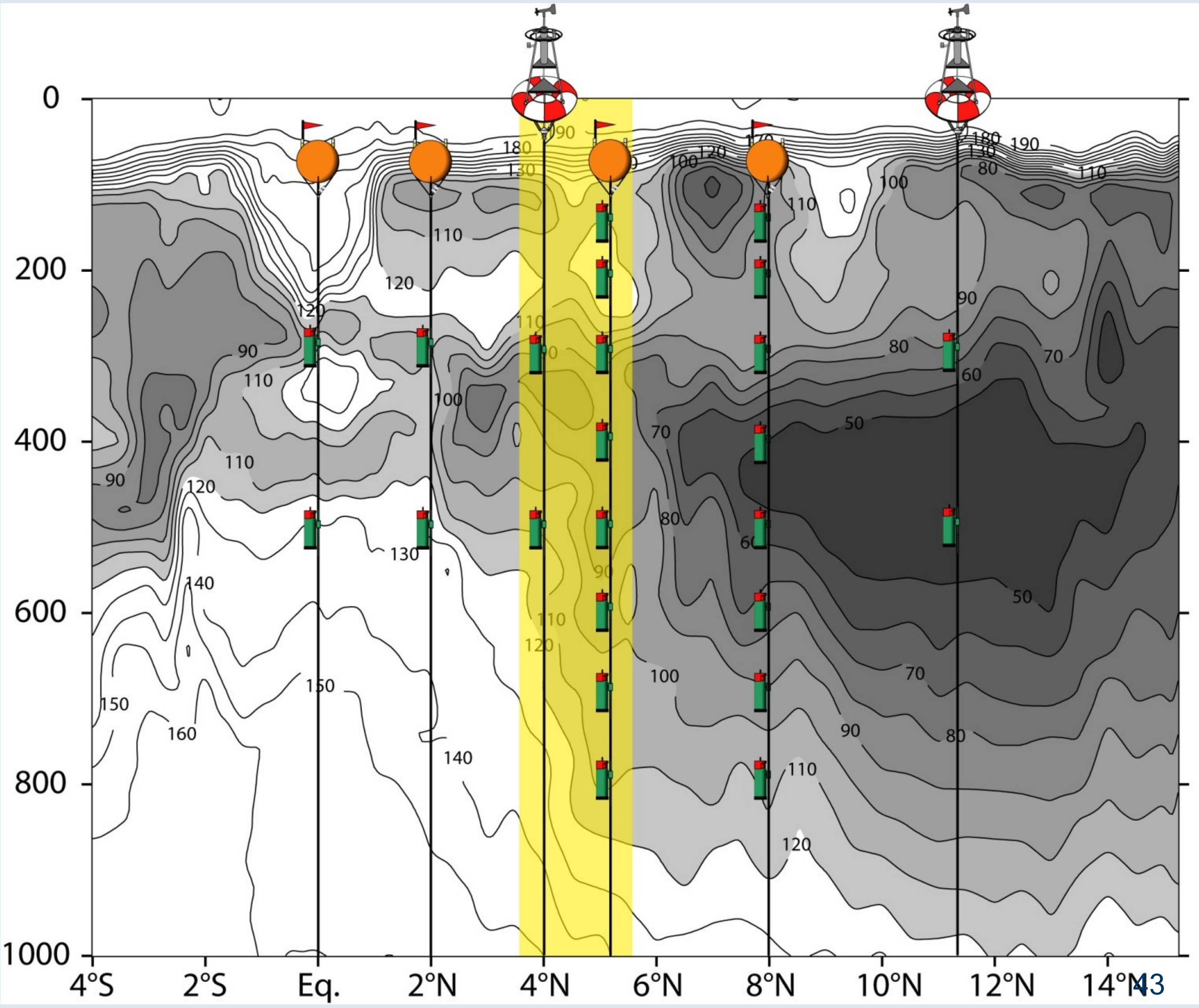
Oxygen variance observed from gliders and moored instruments



Outlook

Observing system as deployed in 2009.

Yellow bar marks region, for which enhanced observations of eddy mixing processes are proposed.



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Thank you
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